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Resource Modelling in a Circular Economy Context

Applying and comparing circular economy indicators and dynamic material flow analysis

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Abstract

The concept of the circular economy (CE) is increasingly suggested as a means of reducing environmental impacts and resource use of production and consumption through CE strategies like reuse, remanufacturing, and recycling. However, an increase in “circularity” does not guarantee an improvement in the use of resources over the lifecycle of a product. Transitions towards a more circular economy therefore need to be supported by quantitative assessments that can guide companies and policymakers in choosing appropriate strategies to implement. However, different methods vary in terms of their scope and focus, and therefore convey different types of information about the system investigated. This thesis aims to contribute towards improved knowledge about a number of methods that can evaluate how CE strategies affect resource use, specifically focusing on CE indicators and dynamic material flow analysis (MFA).

The work presented builds on two studies. Article I is a review and mapping of the flows and processes that CE indicators capture in the product lifecycle. The indicators are also applied to a wide number of cases to determine how the indicators differ and to identify their potential limitations. In article II a dynamic MFA model is developed and applied to a multiple reuse and recycling case of lithium-ion batteries. The study examines how this circular solution could affect raw material and battery flows over time. Finally, the two studies are synthesised into a method comparison of CE indicators and dynamic MFA. The comparison focuses on similarities and differences between the methods with regards to the object of study, how temporal aspects are represented, system boundaries, and the type of results provided. While CE indicators provide information on variations of resource use over the product lifecycle, dynamic MFA informs on how CE strategies can affect stocks and flows of products and materials over time. Amongst other things, the results emphasise the importance of capturing the temporal dynamics of material flows when evaluating CE strategies, e.g. how the availability of secondary resources could change over time or assessing how a transition towards a more circular economy can play out over time.

Keywords: Circular economy, resources, indicators, dynamic material flow analysis

List of included papers

This work primarily builds on the work presented in two articles.

Article I

Jerome, A., Helander, H., Ljunggren, M., Janssen, M. 2022. Mapping and testing circular economy product-level indicators: a critical review. *Resources, Conservation and Recycling* (Vol. 178). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2021.106080

Article II

Helander, H., Ljunggren, M. 2023. *Analysing the dynamics of reuse and recycling in a battery as service case.* Manuscript submitted for publication.

Other related papers

Helander, H., Jerome, A., Ljunggren, M., Janssen, M. 2021. What do product-level circular economy indicators measure? Paper presented at the 4th PLATE 2021 Virtual Conference. 26-28 May 2021

Jerome, A., Helander, H., Ljunggren, M., Janssen, M. 2021. Testing product-level indicators for a more circular economy. Paper presented at the 4th PLATE 2021 Virtual Conference. 26-28 May 2021.

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Articles I & II

1 Introduction

Economic development and population growth have led to unsustainable levels of resource use and associated environmental issues, particularly over the last half-century (IPCC, 2022; Krausmann et al., 2009). Resources are fundamental to the functioning of our socio-economic system and to the creation of human wealth and prosperity—but the current scale of extraction, processing, use, and disposal of resources is also causing severe environmental problems. For instance, the extraction and processing of natural resources is the cause of over half of global greenhouse gas emissions (IRP, 2019). Continuing on these excessive levels of resource use is also of concern due to the harmful effects on vulnerable ecosystems, human rights, and other social justice issues associated with mining, as well as the risk of resource depletion in the future (Henckens et al., 2016; Luckeneder et al., 2021; Tsurukawa et al., 2011). An improved management of resources is also of strategic and economic concern for companies and countries alike since it can minimise supply risks and increase competitiveness. For these reasons, there is a pressing need to transition to more sustainable production and consumption practices.

One part of such a transition increasingly suggested within policymaking, business, and the academic literature is the concept of the circular economy (CE) (Calisto Friant et al., 2020; Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017). A principle aim of the CE is to reduce resource use and environmental impacts of production and consumption through various CE strategies like reuse, remanufacturing, recycling, and improving the durability of products.

However, making products or business models more circular does not lead to resource use reductions by default. CE strategies can, for instance, lead to burden shifts between different life cycle phases or can come at the cost of requiring more materials—e.g. when a product is made more durable (Böckin et al., 2020). Additionally, many CE strategies involve circulating resources over time in various ways, e.g. reusing products or recycling materials. The potential resource effects of, and the appropriateness of implementing, a certain circular solution will then depend on the quantities, types, and timings of resources that become available for secondary use. This, in turn, depends on, e.g. product lifetimes, market demand, whether product designs change, or the speed of technology development.

To understand how resource use could be affected by circular solutions, quantitative evaluations are needed. Evaluations can support the transition towards a more circular economy by determining the CE strategies that are most effective at reducing resource use in different contexts. These can be used by companies to compare design changes of products, to support circular business model implementation, or to inform policymaking (Mayer et al., 2019; Roos Lindgreen et al., 2022).

Several methods have been used for evaluating the impacts of CE strategies on resource use and environmental impacts (Sassanelli et al., 2019; Walzberg et al., 2021). Focusing specifically on resources, material flow analysis (MFA) is a commonly used method (Haas et al., 2015; Tecchio et al., 2018). Drawing on MFA thinking, a large number of product-level CE indicators have been presented in the literature in recent years, with the specific purpose of evaluating resource use at the product level (Corona et al., 2019; Kristensen & Mosgaard, 2020). Dynamic MFA, a method for modelling anthropogenic stocks and flows of materials over time (Baccini & Bader, 1996), can also be used to evaluate resource use in a CE context. It has lately been applied to evaluate a broad range of CE strategies, e.g. product reuse and remanufacturing (Aguilar Lopez et al., 2022; Khalifa et al., 2021).

Methods vary in terms of scope and focus, and thus convey different types of information. Such differences could have implications for the appropriate contexts in which they can be used and the types of questions they are suitable for addressing. Previous studies have critically reviewed a number of assessment methods for the CE to clarify the differences between them, and to identify their strengths and weaknesses—focusing on how they account for environmental, social, and economic sustainability (Sassanelli et al., 2019; Walzberg et al., 2021). However, a close examination of methods that specifically evaluate resource use in a CE context is lacking. To facilitate a better understanding of how resources are affected by CE strategies and how this can be measured, there is a need to examine and compare methods that focus on resource use. Such an investigation could provide insights regarding method selection, development and use by pointing to potential limitations of existing methods. Thus, the aim of this licentiate thesis is to contribute to knowledge about methods that evaluate how CE strategies could affect resource use. This is carried out through a method comparison of product-level CE indicators and dynamic MFA. The work consists of two articles and a synthesis of these, presented in the Kappa. Article I is a review and mapping of product-level CE indicators, which are also applied on a wide number of CE cases. In article II, a dynamic MFA model is developed and applied to a reuse and recycling case of lithium-ion batteries. In the Kappa, the two articles are synthesised into a method comparison of product-level CE indicators and dynamic MFA.

2 Background

The focus here is on the study of resources. To discuss the study of resources, it is necessary to grasp concepts related to resources as such, strategies for resource management, and assessment methods that can guide the improved management of these. The following sections describe current resource challenges, the CE as a response to these challenges, and methods for evaluating resource use.

2.1 Resource challenges and the importance of studying them

The extraction, processing, use, and disposal of resources cause various environmental impacts, but they are also of concern due to risks associated with depletion, supply, and price volatility. Furthermore, mining could lead to both environmental and social harm in local communities. Studying resources is thus of interest for environmental, social, and economic reasons, which are explored further below.

Natural resources provide the foundations for the goods, services, and infrastructure that make up our socio-economic system. Many definitions exist. For instance, the Oxford Dictionary (2022) refers to natural resources as “naturally occurring substances that serve as inputs for industrial and consumptive uses”. These include metals, minerals, fossil fuels, and biomass, as well as water, land, solar radiation, and wind. Sometimes a distinction is made between natural resources and the primary raw materials or energy carriers that are the results of various levels of processing of natural resources by the primary extraction sector (Sonderegger et al., 2017). However, this distinction is not always made since most resources require some level of processing before they are used as inputs for production, or consumed (IRP, 2019). Primary raw materials are those derived from natural resources, while secondary materials are obtained from anthropogenic sources, e.g. from products that have reached end-of-life. Resource use in the context applied here concerns the study of stocks or flows of material resources, including both primary and secondary raw materials. It is important to note that this is different from studying the environmental impacts associated with the use of resources, as is done with life cycle assessment (LCA). In LCA, material and energy flows and emissions are instead translated into their potential contribution to various environmental impacts. Furthermore, the term resources as used here should be distinguished from resources as understood in economics, which includes any source or supply from which value can be produced, e.g. human or financial resources, equipment, and machinery etc.

Different categories of resources are subject to different issues and concerns. A common distinction is made between four major resource categories: metals, non-metallic minerals, fossil fuels, and biomass (Wiedenhofer et al., 2019). The first three are non-renewable, i.e. they are regarded as exhaustible. Whether this exhaustibility will lead to resource depletion for human use remains an open question (Ericsson et al., 2019; Henckens et al., 2016). Gradually declining ore grades of various minerals have led to concerns regarding such possibilities over the medium to long term (Teseletso & Adachi, 2021). However, it has been argued that when declining ore grades have been observed, this has primarily been the result of economic factors such as high demand and improved technology—which enables extraction of increasingly lower grade deposits (Ericsson et al., 2019). The grades of mined ore are thus ultimately a relationship between costs and revenues, and future detection of higher-grade ores cannot be ruled out. Regardless of the possibility of scarcity; extraction and processing activities of metals and minerals cause many other concerns like threats to vulnerable ecosystems (Luckeneder et al., 2021), climate change impacts, and human rights issues (Tsurukawa et al., 2011). In the second half of the 20th century, the risks of exhaustibility of fossil fuels led to a debate about the potential of reaching "peak oil" (Bardi, 2019). However, the current consensus is that climate change, rather than absolute scarcity concerns, will impose limits on fossil fuel use (Verbruggen & Marchohi, 2010). Biomass resources are renewable but could be exhaustible if overused, and the current extensive use of biomass globally is subject to a number of environmental and human-health issues (IRP, 2019). For instance, the extraction of biomass is the cause of close to a fifth of global climate change impacts and over 80% of global land-use related biodiversity loss.

Current levels of resource use and the expected increase in coming decades is also an economic and strategic concern for countries and companies. The concept of critical raw materials have been used to describe those that are considered to have high probability of supply disruption and where specific actors are vulnerable to that disruption (Dewulf et al., 2016). This could for instance be due to rapidly increasing demands for certain materials where it is difficult to expand production infrastructure at similar rates, which could lead to supply bottlenecks (Valero et al., 2018). Another example concerns materials where production capacities are geographically concentrated, which could make supply chains vulnerable and lead to price volatilities and bottlenecks (Bleischwitz et al., 2014).

2.2 Circular economy as a response to current resource challenges

To address the resource challenges summarised above, the CE concept has been suggested as a solution. The idea has been gaining increasing attention within the business community, policymaking, and academia over the last decade (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017). It can be viewed as an umbrella concept that collects a number of already existing concepts into a new framing (Blomsma & Brennan, 2017). The definitions of the CE concept diverge (Kirchherr et al., 2017), but it is widely understood as a way of reducing resource use and environmental impacts of production and consumption (Geissdoerfer et al., 2017). CE concepts proposed include extending resource life (Blomsma & Brennan, 2017); closing, slowing, and narrowing resource loops (Bocken et al., 2016); or retaining resource value (Reike et al., 2018). Additional reasons for transitioning to a more circular economy include: increasing economic growth and revenue streams for companies (Ellen MacArthur Foundation, 2013), securing access to strategically important materials (Benton et al., 2015), or to deliver transformational changes to the current socio-political system (Hobson & Lynch, 2016). No matter how the end-goals of the CE concept are understood, the means to reach the stated aims are through various CE strategies like reuse, remanufacturing, recycling, and improving the durability of products. Implementation of such CE strategies is underpinned by, e.g. product design changes, new business models, public policy, and changes in consumption practices (Bocken et al., 2016; Ghisellini et al., 2016).

The meaning of several specific CE strategies is poorly defined. For instance, Reike et al. (2018) noted 38 different "R-terms" (e.g. reuse, repair, remanufacture, refurbish, renovate etc.) many of which are understood to mean different things by different authors. Here, the typology of 18 physical measures suggested by Böckin et al. (2020) is used (Figure 1), hereafter referred to as CE strategies. The typology outlines CE strategies that are suitable at different phases of the product life cycle, which are organised around four different strategy groups, targeting: 1) extraction and production, 2) effectiveness and efficiency during use, 3) extended use of products, and 4) end-of-life.

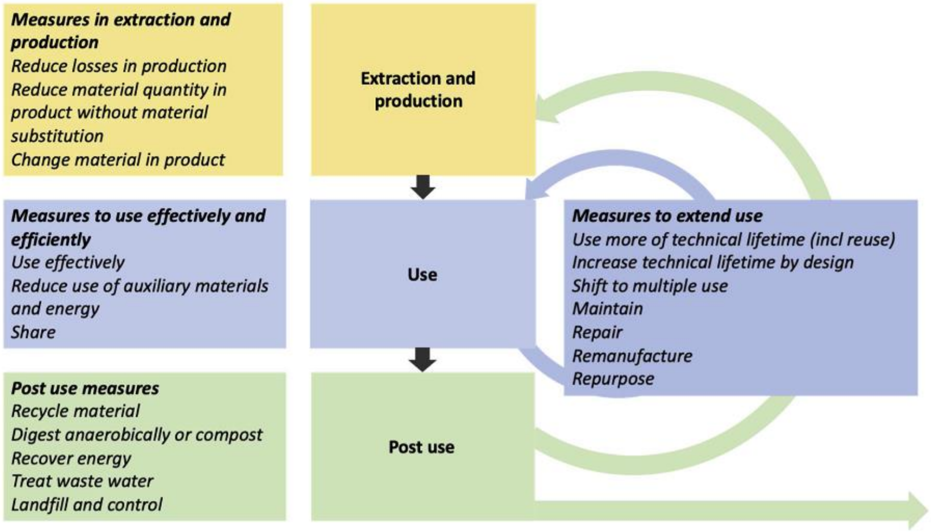


Figure 1. Typology of 18 physical circular economy strategies from Böckin et al. (2020).

Since CE strategies point to several opportunities for extending resource life, it could be challenging to understand how resource use could be affected and therefore difficult to decide on the appropriate strategies to implement. For instance, the suitability of a CE strategy and its effect on resource use might depend on the product characteristics and surrounding context in which the strategy is implemented (Böckin et al., 2020). As an example, decreasing the material quantity in a product could lead to lifetime reductions, which requires an overall increase in production to maintain the original function provided by the product. Alternatively, a more durable product could require a shift to different types of, or more, materials used in its production (Ljunggren Söderman & André, 2019). Furthermore, many CE strategies involve circulating resources over time, e.g. reusing products and components, recycling material, or performing lifetime extensions like repair and remanufacturing. The effect on resource use from implementing CE strategies will then depend on the quantities of secondary resources becoming available at certain points in time (Haupt et al., 2017). Additionally, a transition towards more circular production and consumption practices is something that would occur over time (Ghisellini & Ulgiati, 2020). Product lifetimes, design changes, market demand, and speed of technology development could then affect the availability and demand for secondary resources over time (Bakker et al., 2021; Guzzo et al., 2021). In light of the rapid reductions of greenhouse gas emissions required to reach internationally agreed limits (IPCC, 2022)—which the CE partly is a response to—it is also relevant to consider the temporal aspects of transitions towards a more circular economy. For instance, how quickly would CE strategies need to be in place to reach a certain outcome, or how does the speed of adoption of a circular business model affect its potentials to reduce resource use (Sigüenza et al., 2020). Thus, it is important for companies and policymakers, from both a planning and evaluation perspective, to understand the temporal developments of resource flows and how CE strategies could affect these (Eriksen et al., 2020; Zeiss et al., 2021).

2.3 Methods for evaluating resource use in a circular economy

As pointed out above, whether, or the extent to which, CE strategies reduce resource use cannot be taken for granted. Quantitative evaluations are therefore needed to support the decision of which CE strategy, or combination of strategies, to implement. Evaluations can, e.g. inform product designers or managers in companies, be used to develop policy targets, or be used by researchers to determine the contexts in which specific CE strategies could generate synergies or trade-offs (Blomsma & Brennan, 2017; Roos Lindgreen et al., 2022). A number of methods have been used for such purposes, e.g. LCA, environmentally extended input-output analysis (EE-IO), MFA, and various CE indicators (Harris et al., 2021; Sassanelli et al., 2019; Walzberg et al., 2021). LCA is used to assess the environmental impacts of products and services. This could concern resource use as when quantifying resource depletion impacts (Sonderegger et al., 2017), but could also involve various other environmental impacts. EE-IO has an economywide scope and connects economic output with environmental pressures, which can then be traced along industrial sectors (Wiebe et al., 2019). It thereby has the benefit of being able to capture material flows across international supply chains but requires aggregating these to the level of product groups or sectors.

For specifically studying material resources at a more granular level, MFA is a commonly used method (Brunner & Rechberger, 2017). MFA does not account for environmental impacts but is used for tracing and quantifying stocks and flows of material resources. It has been applied to analyse the CE, e.g. at the global (Haas et al., 2015), citywide (Voskamp et al., 2017), or product-system level (Tecchio et al., 2018). While MFA traditionally is focused on a stationary description and analysis, dynamic MFA involves a time-dependent model of inflows, outflows, and stocks of materials (Baccini & Bader, 1996; D. Müller, 2006). It has recently been applied to evaluate CE strategies in different contexts, for different materials, and product types (Busch et al., 2014; Pauliuk et al., 2021; Sigüenza et al., 2020; Zhang et al., 2021). An additional method for evaluating resources in a CE context is through the use of indicators. A number of resource-based CE indicators have been presented in literature, in which different flows of materials over the life cycle of a product are quantified (Ardente & Mathieux, 2014; Bracquené et al., 2020; Ellen MacArthur Foundation, 2015; Lokesh et al., 2020). These CE indicators can be used to quantify resource use in a CE context with the advantage of being relatively easy to compute and communicate.

Previous studies have reviewed methods used to evaluate the CE (Sassanelli et al., 2019; Walzberg et al., 2021). Sassanelli et al. (2019) reviewed existing methods and analysed the type of data they require and the sustainability dimensions they address: environmental, social, and economic. However, the authors provide no information regarding their differences in terms of scope of the analysis or other key methodological considerations. Walzberg et al. (2021) critically reviewed and compared a number of assessment methods in order to provide guidelines to CE researchers, policymakers, and companies regarding their use. This included the method scope, data requirements, how they account for temporal aspects, and how they can be applied to measure different dimensions of sustainability. These studies have a broad focus and include methods that evaluate the CE from an environmental, energy, resource, and economic perspective. However, a close examination of methods that specifically evaluate resource use in a CE context is lacking. Furthermore, no study that have reviewed different CE assessment methods have included product-level CE indicators or dynamic

MFA in their analyses. Since these two methods are commonly used for evaluating resource use in a CE context in various ways, providing deeper knowledge about the key differences and similarities between them could be useful for both method users and developers—active in companies or within research. A structured comparison of the methods could then contribute to a more systematised understanding about them. Such an exploration could shed light on the type of information they can provide and how this differs. This has implications for the appropriate contexts in which they could be used, can point to limitations and strengths, and can aid selection and further method development.

These two methods are explored in further detail below, including previous reviews of product-level indicators, and the ways in which dynamic MFA has been applied to evaluate the CE.

2.3.1 Product-level circular economy indicators

Assessments of resource use at the product-level are important for understanding how changes to a product portfolio could affect resource use over the life cycle. It could support decision-making of what CE strategies to implement, or be used by companies for communicating with customers or suppliers. Several CE indicators have been presented in the literature (Saidani et al., 2019), which can be used by companies to measure and monitor the CE at the product-level.

A number of product-level CE indicator reviews have been carried out to compare and analyse existing CE indicators. This has revealed, amongst other things, that there is no standardised way of measuring the CE (De Pascale et al., 2021). Kristensen & Mosgaard (2020) identified 30 product-level CE indicators and classified them according to how they align with the three sustainability dimensions and the type of data they require. Helander et al. (2019) analysed a sample of 10 CE indicators and found that these often only capture parts of a product’s life cycle. Moraga et al. (2019) created a classification framework based on whether CE indicators assess products, components, materials, or energy, and evaluated the extent to which the authors interpret the CE indicators to incorporate life cycle thinking. They conclude that most indicators are limited in this regard. A consequence of the broadness of the CE concept is that ‘circularity’ can mean different things, which means that it is unclear what existing CE indicators de facto quantify over the life cycle. A deeper understanding of what indicators quantify and how they diverge is partly explained by a lack of testing indicators on cases. Only one indicator review tested a limited number of product-level indicators on a case and concluded that these were unable to grasp all CE strategies (Saidani et al., 2017). Consequently, a clear description of what CE indicators specifically quantify over the life cycle is lacking. Furthermore, it has been pointed out that further research is needed to identify complementarities between CE indicators and other assessment methods (Corona et al., 2019; Helander et al., 2019). Another assessment method, which can also be applied to evaluate how CE strategies affect resource use, is dynamic MFA.

2.3.2 Dynamic material flow analysis

MFA is a systematic assessment of the material stocks and flows of a system defined in space and time (Brunner & Rechberger, 2017). It can be used for analysing the sources, pathways, and sinks of substances or materials at various levels, e.g. analysing global material flows (Krausmann et al., 2009), electronic waste management systems (Islam & Huda, 2019), or metal flows at the product-level (Ljunggren Söderman & André, 2019). While MFA involves a stationary description and analysis, dynamic MFA is a time-dependent model of inflows, outflows, and stocks of materials (Baccini & Bader, 1996; D. Müller, 2006). This enables an investigation into historical resource patterns over time, exploration of socio-economic drivers to material use, or the development of scenarios to assess plausible future developments of material stocks and flows (Augiseau & Barles, 2017; Chen & Graedel, 2012; E. Müller et al., 2014). The insights provided can, e.g. guide policymakers or industry stakeholders in planning for investments in production or waste infrastructure, setting policy targets, or for quantifications of material stocks that could be become sources of secondary materials (Lanau et al., 2019; D. Müller, 2006).

Dynamic MFA models vary in their temporal scope, units of measurement, and the processes or end-use sectors included in the analysis (E. Müller et al., 2014). They can be retrospective; focusing on historical dynamics, or prospective; analysing future developments. The time that a stock remains in use is determined using a lifetime function. This function often takes the form of a lifetime distribution or survival rate, which links inflows and outflows over time. A common distinction is made between inflow-driven or stock-driven modelling approaches (Chen & Graedel, 2015; Wiedenhofer et al., 2019). In inflow-driven models, the inflows are exogenous (i.e. input data in the model) which are combined with a lifetime function to derive outflows and stocks over time (i.e. the endogenous, or calculated, outputs of the model). In stock-driven models the in-use stocks are conceptualised as cohorts of service units, which are exogenous to the model. These are then used to calculate the required inflows, from which the outflows of each cohort can be determined using a lifetime function (D. Müller, 2006).

A number of dynamic MFA studies have evaluated how CE strategies could affect resource use. The focus is often on the materials in one or several end-use sectors evaluated at the national, regional, or global level (an overview of dynamic MFA studies that have evaluated different CE strategies is provided in Table 1). For instance, Løvik et al. (2014) investigated different recycling strategies to reduce scrap surplus from aluminium in vehicles. This is done with a model that distinguishes between different vehicle components and the aluminium-alloys contained in these. Various model parameters, e.g. the share of components dismantled at end-of-life, are then altered to determine the effects on scrap surplus in the future. Zhang et al. (2021) provides another example of how recycling has been addressed. They evaluated the extent to which secondary materials can meet demand in the construction sector. This is done by comparing the forecasted materials from building demolitions and renovations (model outflows) with projected building constructions (inflows). Other CE strategies, e.g. material substitutions, reuse, or technical lifetime improvements can also be evaluated by adapting dynamic MFA models in different ways. Material substitution scenarios have been investigated by changing the material composition of the inflows to reflect plausible future changes, e.g. for electric vehicles (Baars et al., 2021). Busch et al. (2014) explored different levels of vehicle battery reuse through a nested description of vehicles and their batteries, using separate lifetime functions. Both outflows of vehicles and batteries could then be traced over time. Technical lifetime improvements can be investigated by altering the lifetime function of the in-use stocks. For instance, Wang et al. (2018) explored the effect on steel demand from lifetime changes of steel in four major product groups. The implications of introducing circular business models or changing customer preferences have also been investigated. For instance, Kamran et al. (2021) investigated how battery metal demand could be affected by a transition towards sharing-based circular business model. They assume that an increasing part of the transport-km demanded in a country is met by car sharing services, which have higher yearly mileages than privately owned vehicles. The service-level of the in-use stock is then met with fewer vehicles, but these have shorter lifetimes since they are used more intensely.

2.4 Summary of background

In summary, as a response to current resource challenges, the CE has been suggested as a solution. The CE includes multiple strategies that aim to reduce resource use of production and consumption. To understand how resource use could be affected by CE strategies, quantitative evaluations are needed. These can, e.g. be used by companies to assess design changes of products, to support circular business model implementation, or to inform policymaking. Several methods can be used for such purposes, which provide different types of information and could be suitable in different contexts. While previous studies have reviewed and compared a number of methods used to evaluate the CE, these have largely focused on how methods can evaluate the environmental, social, and economic sustainability impacts of the CE. A close examination of methods that specifically evaluate material resources use is, however, lacking. In particular, previous method comparisons have not included product-level CE indicators and dynamic MFA in their analyses, both of which can be used for evaluating how the resource use of products can be affected by CE strategies. Providing deeper knowledge about the key differences and similarities between them could thus be useful for both method users and developers. In particular, a structured method comparison could shed light on the type of information the methods can provide, and can aid both method selection and development.

Table 1. Examples of dynamic MFA studies that have investigated circular economy strategies. Abbreviation: Reg, regional; Nat, national; UK, United Kingdom, EU, European Union; NL, Netherlands; GER, Germany; US, United States; Co, cobalt; Li, lithium; Nd, neodymium; Pt, platinum; Al, aluminium; Cu, copper; PE, polyethylene; PP, polypropylene; PET, polyethylene terephthalate; Ni, nickel; EVs, electric vehicles; LiBs, lithium-ion batteries.

Purpose	**CE strategies**	**Material, product types**	**Includes circular business models**	**Geographical scope**			**Temporal scope**	**Modelling approach**	**Reference**
				Global	Reg	Nat			
Assessing material demands of infrastructure transition	Reuse, recycle	Co, Li, Nd, Pt in passenger vehicles				X (UK)	2020-2050	Stock-driven	(Busch et al., 2014)
Exploring recycling paths of Al in cars and possible interventions to mitigate scrap surplus	Recycle	Al, in passenger vehicles		X			2010-2050	Stock-driven	(Løvik et al., 2014)
Investigate the role of manufacturing in achieving a CE over the long term	Reduce losses in production, increase technical lifetime, share, recycle, reuse, remanufacture	Steel, four end-use sectors: construction, vehicles, machinery, durable goods		X			2013-2100	Stock-driven	(Wang et al., 2018)
Estimating global copper demand until 2100	Recycle	Cu, in multiple end-use sectors		X			2015-2100	Stock-driven	(Schipper et al., 2018)
Assessing material demand and storage capacity of second-use batteries in EU	Reuse, recycle	Co, Li in LiBs			X (EU)		2005-2035	Inflow-driven	(Bobba et al., 2019)
Evaluating the potential circularity of three types of plastic flows, reflecting, e.g. design-for-recycling and increased collection	Recycle	PE, PP, PET			X (EU)		2016-2065	Inflow-driven	(Eriksen et al., 2020)
Investigate material demand of PVs in the USA when different CE strategies are implemented	Recycle, reuse, remanufacture.	Glass, Al, in Photovoltaics				X (US)	2000-2100	Stock-driven	(Khalifa et al., 2021)
Assess battery energy storage capacities and extent to which recycling and sharing can reduce demand for battery materials	Reuse, share, recycle	Ni, Mn, Co, Li, in LiBs	X			X (UK)	2020-2050	Stock-driven	(Kamran et al., 2021)
Illustrate how CE strategies can affect material demand	Reduce material quantity, change material, reuse, recycle	Co, in passenger vehicles	X		X (EU)		2020-2050	Inflow-driven	(Baars et al., 2021)
Material evaluation of adoption of two circular business models	Share, maintain, use effectively	Washing machines	X			X (NL)	2020-2050	Stock-driven	(Sigüenza et al., 2021)
Explore how a novel recycling technology can reduce primary material in the building sector	Recycle	Mineral wool, glass, and lightweight concrete, in buildings				X (NL)	2020-2050	Stock-driven	(Zhang et al., 2021)
Explore the environmental impacts of setting reuse targets for washing machines	Reuse, recycle	Washing machines				X (GER)	2020-2050	Stock-driven	(Boldoczki et al., 2021)
Explore extent to which recycling and battery technology advancement can alleviate Co supply shortages	Change material, recycle, increase technical lifetime	Co, in LiBs		X			1998-2050	Stock-driven	(Zeng et al., 2022)
Illustrate a product-component reuse framework on EVs and LiBs	Reuse	No. of LiBs and EVs		X			2020-2050	Stock-driven	(Aguilar Lopez et al., 2022)

3 Research design

The aim of this licentiate thesis is to contribute to knowledge about methods that evaluate how CE strategies could affect resource use. This is done by comparing product-level CE indicators and dynamic MFA. The comparison explores inherent differences and similarities between the two methods, as well as how they can be used to evaluate CE strategies. The implications of the comparison are discussed and recommendations for method use and potential further development is provided. This could provide useful information for actors seeking to assess how CE strategies affect resource use, e.g. within companies, for policymaking, or research.

The comparison builds on the work presented in two articles. In article I, resource-based product-level CE indicators were reviewed, and the resource flows and processes the indicators capture along the product life cycle were mapped on a generic flowchart model. The purpose of the study was to clarify the differences between the resource flows and processes the CE indicators quantify, to analyse how their results differ when applied to the same cases, and to identify and discuss their limitations. In article II, a dynamic MFA model was developed and applied to a circular business model that involves multiple reuse and recycling of lithium-ion batteries through a product-service system. The main purpose of the study was to investigate the potential effects from such a system on raw materials and product flows over time. Here, the learnings from the two articles are synthesised and structured into a method comparison between CE indicators and dynamic MFA.

3.1 Comparative framework

An analytical framework is first developed which the methods are evaluated and compared against. Differences and similarities of the methods with regards to the aspects in the analytical framework are then identified. Furthermore, implications for methods use and development are discussed, as well as pointing to avenues for further research.

Methods can be described and evaluated with regards to different methodological features or characteristics. For instance, Baumann & Cowell (1999) constructed a comparative framework that addresses contextual and methodological aspects of different environmental management approaches or methods. The contextual aspects they propose concern the situation in which a method is used, for instance the type of decision-maker using the method, the purpose of analysis, and the objects analysed. Methodological aspects concern the method itself and include, for instance, the type of results, the system boundaries, and sustainability dimensions addressed. Walzberg et al. (2021) categorised a number of methods that evaluate the CE, focusing on: the scope of the system covered, how temporal aspects are considered, and the extent to which the method can quantitatively assess the CE against the three dimensions of sustainability. Finnveden & Moberg (2005) characterised a number of tools and methods with regards to their objects of study and the types of impacts considered, e.g. if environmental or economic aspects are included.

The objective here is not to construct an encompassing framework that covers all possible points of comparison for the two methods. Instead, the purpose is to point to a number of aspects identified as important for the outcomes of the assessments carried out with CE indicators and dynamic MFA in the two articles in this licentiate thesis. The comparison focuses on four aspects:

1) The object of study:

The first aspect concerns the object(s) studied with the two methods. CE strategies are often discussed with regards to the level of analysis at which they are implemented. A distinction is then made between the micro (products, companies), meso (eco-industrial parks), and macro (cities, countries) levels. Consequently, the objects studied with CE assessment methods are sometimes discussed in these terms (Harris et al., 2021; Moraga et al., 2019). However, these are broad distinctions, the differences of which are not entirely clear (Corona et al., 2019). A more detailed categorisation is therefore proposed here, focusing on the specific unit of analysis and the technical system considered when applying the method.

2) Representation of time:

Many circular strategies involve the circulation of products, components, and materials over time (Bocken et al., 2016) and, as outlined in section 2, CE strategies aim to *extend resource life* (Blomsma & Brennan, 2017). Furthermore, potential transitions towards a more circular economy is something that will occur over time (Ghisellini & Ulgiati, 2020). Thus, when resource flows occur and how temporal aspects can impact the resource use implications of circular solutions are therefore important to understand. Consequently, Walzberg et al. (2021) characterised a number of CE assessment methods with regards to the temporal scale of the assessments carried out with these. Here, a comparison is made between how the two methods represent time.

3) Other system boundaries:

The system boundaries define the 'realm' of the model (Baumann & Cowell, 1999). The first two aspects in the framework address the technical system considered and the temporal boundaries of both methods. The third aspect concerns how the two methods compare with regards to other system boundaries, like those regarding the organisational or spatial boundaries of the investigated system.

4) Type of results:

The final aspect addresses what type of results the methods can provide. While both methods provide quantitative output data, the character of these have implications the type of insights that can be gained from the use of each method.

3.2 Materials

The comparison was informed by: 1) the review, mapping, and application of existing CE indicators on a number of cases, carried out in article I; 2) the development of a dynamic MFA model and application of the model on a multiple reuse and recycling case of lithium-ion batteries, which was carried out in article II; and 3) a selection of literature of dynamic MFA studies that evaluate the resource use implications of various CE strategies (see Table 1). The studies included are not an exhaustive representation of the available literature but a selection of studies that investigate strategies like, reuse, remanufacturing, recycling, increase technical lifetime by design, sharing, and reduction of material production losses. It should be noted that the comparison is thus based on the selection of

CE indicators reviewed in article I (see Table 2 in article I for an overview of the indicators), the dynamic MFA model developed in article II, as well as the dynamic MFA studies presented in Table 1.

The following section briefly describes articles I and II.

3.2.1 Article I

In article I, the data requirements, method descriptions, and equations for calculating 36 indicators from 16 publications were analysed. This information was used to construct a generic flowchart model that illustrates the specific flows and processes over the life cycle which the indicators capture, while offering a straightforward comparison of the indicators. Additionally, to compare the results provided by the indicators, they were applied to seven cases taken from three published LCA studies (André et al., 2019; Böckin & Tillman, 2019; Willskytt & Tillman, 2019). The studies investigate a number of CE strategies applied to three products. These cases cover a range of product characteristics identified by Böckin et al. (2020) as important for the outcome of CE strategies. The product cases are briefly outlined below.

The first product case is about incontinence products used in elderly homes (Willskytt & Tillman, 2019). It involves four different cases covering various CE strategies, which were all assessed separately: case a) increasing recycling of production wastes, case b) changing to more bio-based materials, case c) shifting to multiple use, and case d) using the products more effectively by adapting them to the user. The second product case, case e) investigates lifetime extensions of laptops through reuse (André et al., 2019). The third product case concerns weight reductions of a truck engine through 3D-printing (Böckin & Tillman, 2019). It includes two different cases that were also assessed separately: case f) 3D-printing of an engine using current technology, and case g) 3D-printing of the same engine using a future technology where additional weight reduction is assumed.

The indicators were applied to these seven different cases (a-g). For each case, the implementation of the CE strategies was compared to a business-as-usual alternative. Additionally, the indicator results were compared to the LCA results from the three studies to determine whether these differ. However, since the focus here is delimited to resources and not environmental impacts, results with regards to the latter are outside the scope of what is discussed in the Kappa. See article I for further details about the cases, the results of the indicator testing, and the comparison with LCA results.

3.2.2 Article II

In article II, a dynamic MFA model was developed and applied to analyse the implementation of a circular business model based on reuse and recycling of lithium-ion batteries. The object of study is an underground mining equipment manufacturer that provides batteries-as-a-service, which are used to power a range of different machines. The batteries consist of standardised subpack units that can be combined into battery packs of different sizes. It is then possible to accommodate the machine requirements independent of machine type or size class, using the subpacks as building blocks. Due to differing user needs, intensity of use, and length of operation during one charge, the subpacks are taken out of use at varying levels of degradation depending on the machine they are used in. As a result, it is possible to reuse the batteries across the different machines, and to enable closed-loop recycling at end-of-life. The study investigates the potential effects on material demand and product flows over time from implementing the circular business model until 2050, through scenarios reflecting different levels of reuse and recycling efficiency. While the current business model is only focused on battery reuse within the machines, one scenario concerns the material demands and energy storage capabilities if the business model would be expanded to also include reuse in stationary energy storage applications. The study investigates how resource use related to reuse and recycling changes over time, highlighting limitations and opportunities of these strategies at a company level. See article II for details of the case and the results for each scenario.

4 Results of the comparison

The results of the comparison are presented below, addressing the four aspects included in the comparative framework: the object of study, representation of time, other system boundaries, and the type of results provided.

4.1 Object of study

Both CE indicators and dynamic MFA are used to evaluate the use of resources. The object of study can be separated into the unit of analysis and the technical system considered in the assessment. With CE indicators the unit of analysis is a single product. With dynamic MFA this is instead several product units of one or several product types. The technical system considered in the two methods is not necessarily different but depends on the CE indicator chosen, or in the case of dynamic MFA, the choices made by the analyst which to a large extent is a consequence of the purpose of the study.

The specific resource flows and processes captured by CE indicators diverge significantly. *Single-focus* indicators account for the efficiencies related to specific CE strategies, while m*ulti-focus* indicators combine the effects of various CE strategies into one value, e.g. losses during production, use of recycled material, and recycling rates at end-of-life. The flowchart mapping carried out in article I showed that most indicators quantify a limited part of the life cycle. Figure 2 illustrates the flowchart model constructed in article I that describes the technical system the indicators capture, and how the scope of two of the 36 CE indicators analysed in the article differ (*the recycled content rate indicator, RCR, and product circularity indicator*, *PCI*). *Single-focus* indicators, which address a single CE strategy, capture more limited parts of the system—often flows and processes in one or two life cycle phases (e.g. Figure 2a). In contrast, *multi-focus* indicators generally have a more comprehensive scope and capture more flows and processes (e.g. Figure 2b). As mentioned, the technical system considered in the two methods is not necessarily different. The flowchart model in article I could therefore also represent the technical system boundaries of a dynamic MFA study. For instance, the *RCR* indicator (Figure 2a) is explored year-by-year for batteries in article II (see e.g. Figure 3b).

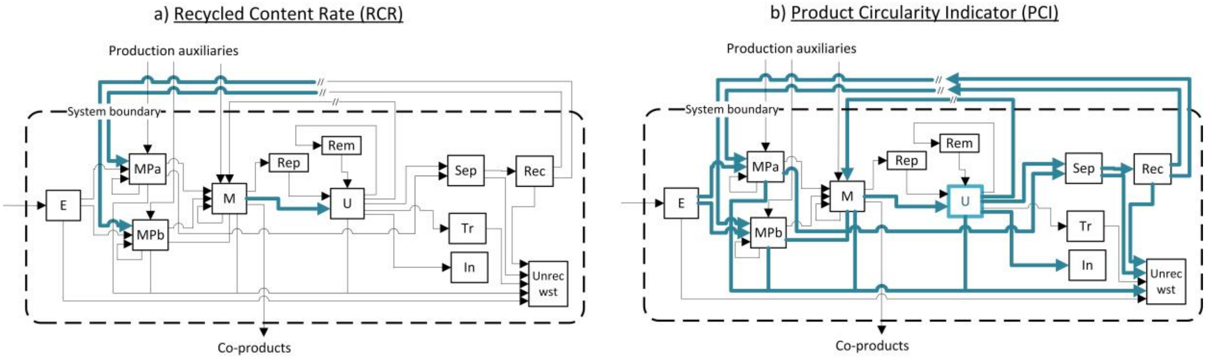


Figure 2. Flowcharts of two of the 36 CE indicators analysed in article I, highlighting the flows and processes each indicator accounts for over the product life cycle (in blue), a) is a single-focus indicator, and b) a multi-focus indicator

The focus in dynamic MFA is an analysis of the in-use stocks of a product, group of products, and materials contained in these within a specific technical system boundary, and the inflows and outflows connected to these. Many dynamic MFA studies model the production phases in a simplified manner, e.g. by not considering losses in refining or production (Bobba et al., 2019; Busch et al., 2014; Kamran et al., 2021), but the granularity of the flows considered depends on the study. For instance, Løvik et al. (2014) account for various material production and recycling processes in a more elaborate way since the purpose of the study is to explore different recycling paths for automotive aluminium. The level of detail of the product types investigated also depends on the study. For instance, Sigüenza et al. (2021) distinguish between three washing machine types that have different lifetimes and maintenance requirements. Baars et al. (2021) consider nine passenger vehicle segments that have different battery characteristics. The level of detail of the end-uses of materials could also be lower. For instance, Wang & Kara (2019) investigate how global steel demand is affected by different CE strategies by considering steel contents in four product categories: construction, vehicles, machinery, and durable goods.

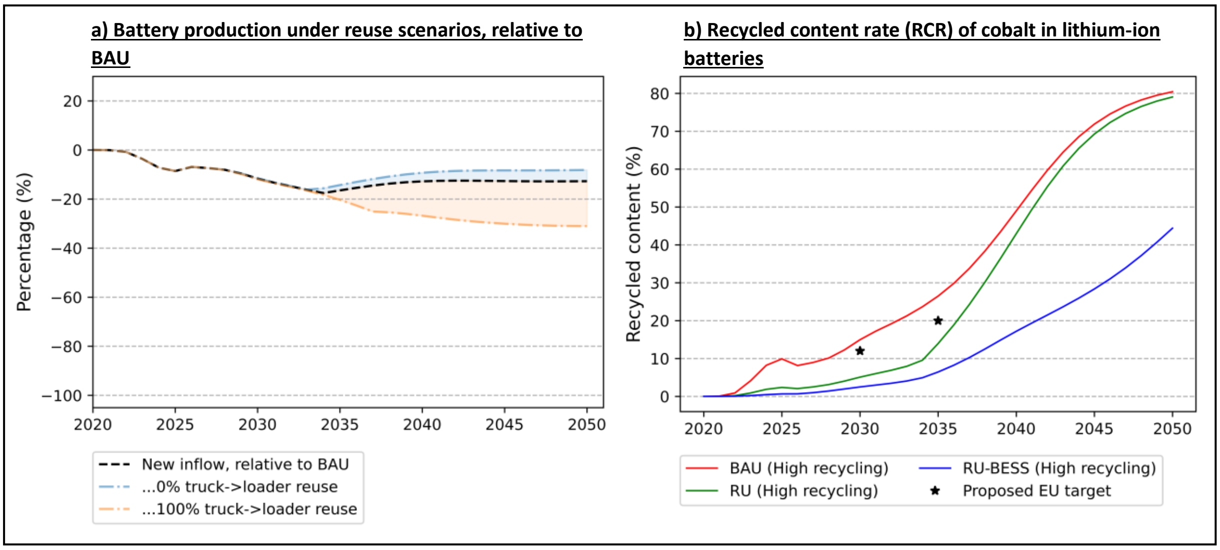
4.2 Representation of time

Temporal aspects are represented in different ways with CE indicators and dynamic MFA. A key difference between the two methods is their temporal resolution, i.e. how many separate time periods that are included in the assessment**.** CE indicators include one time period that encompasses the duration of the life cycle. Some of the *single-focus* indicators can also be used to express the circumstances at a single point in time. This can then be used to construct time series since these indicators quantify a rate or an efficiency of a specific process, e.g. a collection, recycling efficiency, or recycled content rate. Dynamic MFA instead investigates a system over time, which includes several distinct time periods.

The time period included in CE indicators spans the duration of the life cycle, without further resolution in time. Thus, no stocks or stock changes are accumulated in the investigated system since the entire life cycle is treated as a singular time period. The CE indicators then do not distinguish between when different flows or processes occur along the life cycle. For instance, in the second-hand laptop case in article I (case e), the reuse activity also leads to an increase in the share of laptops collected for recycling. This is highlighted as an improvement since the material recycled over the course of the entire life cycle increases. No distinction is made of whether material is recycled after three years (the end of the first use phase) or six years (the end of the second use phase). As a result, any trade-off at a certain point in time between the lifetime extension from the reuse activity and share of material sent to recycling at the end of the first use phase is not captured. An understanding of such a trade-off could, for instance, be relevant from a planning perspective: when does the material become available and when can the recycled material potentially displace, or avoid, primary material demand? These two CE strategies clearly cannot occur at the same time. Instead, in this example, the indicators emphasise the synergy between the two strategies, which results from the resale company's increased collection rate to recycling.

The CE indicators are stationary in the sense that they do not consider when resource flows occur, neither within nor across several product life cycles. For instance, in article I, the CE indicators were applied to a current and potential future design of a 3D-printed truck engine (cases f and g in article I). No information is then provided regarding how, for instance, the end-of-life resource flows of the current product design could be connected to the resource inflows in the future product design. That is, since the scope of the indicators is of a singular product life cycle, the indicators assess the two systems in isolation.

In contrast, dynamic MFA evaluates a system over a period of time, which is accounted for in discrete time steps usually at one-year intervals (Lanau et al., 2019). Product lifetimes are included through a lifetime function, which connects resource outflows to inflows over time. Thus, *when* inflows and outflows occur, and stocks accumulate, are modelled across the different time periods. This enables an analysis of the degree to which primary products or materials can be displaced by the use of secondary sources at a certain point in time. For instance, in article II, the extent to which both the reuse of batteries could displace battery production and the extent to which recycled materials could reduce primary material demand is investigated. Initially, the displacement of new batteries is limited by the low number of secondary batteries available for reuse. Over time the battery stock grows, which results in reused batteries becoming increasingly available to displace new batteries. Eventually, reuse supply is likely to exceed company needs, which also limits the degree to which secondary batteries can displace new ones. The reuse and recycling potentials are then not constant over time but depends on the lifetime dynamics of the products, and the growth and size of the stocks, which affect how the overall inflows and outflows relate to one another. This development can be seen in Figure 3a, which illustrates the battery production under different reuse scenarios, relative to a baseline without reuse. Additionally, when batteries are reused, the availability of recycled material decreases since the stock remains longer in use. Figure 3b shows the potential recycled content of cobalt for three scenarios from article II: one without reuse and two with varying levels of reuse. Such an analysis requires an analysis of how stocks and flows relate to one another over time.


a) Battery production under reuse scenarios, relative to BAU

b) Recycled content rate (RCR) of cobalt in lithium-ion batteries

Figure 3a) the displacement of battery production from reuse relative to a baseline with no reuse, the orange and blue lines correspond to an increase and decrease of share of batteries that are possible to reuse, respectively, adapted from article II. 3b) the recycled content of cobalt with no reuse (red), reuse (green), and additional reuse (blue). See article II for details about the case and the investigated system.

Although the CE indicators account for resource flows and processes over the life cycle, product lifetimes are not necessarily included. Six of the reviewed CE indicators include parameters describing the lifetime of the investigated product (see Table 2 in article I). These parameters affect the final outcomes of the indicators by rewarding a lifetime increase in different ways. In the *Relative Net Loss (RNL)* indicator (Ljunggren Söderman & André, 2019), the share of materials lost (i.e. non-functionally recycled) over the life cycle is expressed relative to the product's service lifetime and provided function. In the *Material Circularity Indicator (MCI)*, *Product Circularity Indicator (PCI)*, and *Material Circularity Indicator for biobased products (MCI-BB)* (Bracquené et al., 2020; Razza et al., 2020), lifetimes are accounted for by benchmarking the investigated product to an industry average. The *Longevity* indicator quantifies the duration that a material is contained in the life cycle of a product, including the product's initial lifetime, remanufacturing, and recycling (Figge et al., 2018). Lastly, the *Specific Energy and Resource Indicator (SERI)* aggregates several parameters related to material inputs, energy demand, and product lifetimes into one value (Winzer et al., 2017). The other indicators account, to varying degrees, for flows and processes over the life cycle without considering product lifetimes. However, as outlined above, CE indicators that for instance include both production and end-of-life does not account for when these activities occur—regardless of the temporal divide between them.

With CE indicators', the time window of the studied system spans the product life cycle, from extraction of raw materials to end-of-life. The temporal scope of the resource flows captured by the indicators is then as long as the lifetime of the evaluated product. In contrast, the time window of a system studied with dynamic MFA is decided by the analyst. It often spans decades but could also cover centuries (Khalifa et al., 2021; Schipper et al., 2018). Both methods can be used retrospectively or prospectively, depending on the purpose of the study.

In brief, the temporal aspects considered in the comparison include: the temporal resolution, whether resource flows are connected over time, consideration of the product lifetime, and the time window of the investigated system.

4.3 Other system boundaries

Apart from the technical system and the time window of the studied system, a distinction is made between the spatial and organisational system boundaries considered with the two methods.

The spatial and organisational system boundaries considered in CE indicators span the geographical area and organisations where extraction, production, use, and end-of-life occur. As a result, the resource flows accounted for are not delimited to a specific spatial or organisational boundary. In contrast, dynamic MFA accounts for the resource stocks and flows within a spatial system boundary that can, e.g. be global, regional, or national. Commonly, national or regional dynamic MFA studies only consider the spatial boundary in terms of the use phase and end-of-life flows, while the locations where extraction or production take place is outside the scope of the study. For instance, Bobba et al. (2019), investigates lithium-ion battery stocks and flows in the European Union. However, where the batteries are manufactured is outside the scope. In article II, the dynamic MFA model has a company perspective. The organisational boundary is then the circular business model of the investigated company, while material and battery production are assumed to occur outside the boundaries of the company, and are not considered in further detail. A number of other dynamic MFA studies evaluate the resource use implications of implementing circular business models. This is done through scenarios where certain shares of national or regional demand is met through leasing or service-based models (Baars et al., 2021; Kamran et al., 2021; Sigüenza et al., 2021). These studies then account for resources within the geographical region considered, but do not investigate the resource dynamics pertaining to one specific organisational boundary.

4.4 Type of results

CE indicators primarily provide information on how CE strategies affect different resource flows across the life cycle. They present results describing variations of resource use over the life cycle of a product, in particular describing the size of resource flows relative to other flows in the system. Dynamic MFA provides results describing absolute quantities of resource stocks and flows and the temporal dynamics of these, e.g. when flows occur or the size of the stock at a certain point in time.

The CE indicators are mainly expressed per product, disregarding attributes related to the function the product provides. However, five indicators also include a parameter describing the product's function. Four of them do this by benchmarking the function to an industry average (*MCI, PCI, MCI-BB, SERI*), and one indicator is expressed per unit of product function (*RNL*). All indicators, apart from *RNL*, is calculated from resource flows relative to other flows within the system. As a result, these indicators provide results describing efficiencies of the flows over the life cycle but do not capture absolute reductions of resource use. Consequently, dematerialisation strategies which reduce the mass associated with a product while maintaining its original function will not be rewarded by most indicators. For both the effective use of incontinence products and the 3D-printed engine (cases d, f, and g in article I), the product mass is reduced while providing the same function. This improvement is only visible from the *RNL* indicator, which is expressed per unit of product function. Using the function as the basis of analysis connects resources with the services these provide, and enables an analysis of whether absolute variations in resource use occur for the delivery of the same product function.

Dynamic MFA provides results describing absolute quantities of flows and stocks, and how these could be affected over time by implementation of CE strategies. Results can also be expressed in relative terms, e.g. recycled content rates or share of total product inflows that come from reuse sources (e.g. article II). Examples of issues explored in dynamic MFA studies include: when recycling infrastructure needs to be in place to reach certain levels of primary material demand (Busch et al., 2014), the extent to which CE strategies can alleviate material supply bottlenecks in the future (Zeng et al., 2022), or how the timing of end-of-life flows are affected by strategies such as reuse and remanufacturing (Khalifa et al., 2021).

In dynamic MFA studies, products can be connected to the functions or services these provide by linking in-use stocks to a certain service-level. For instance, a specific level of person-km per capita travelled by car can be met by individual car ownership or by some degree of car-sharing (Kamran et al., 2021). Stock-driven modelling uses the stock, or the service-level the stock provides, to derive inflows and outflows. This approach enables an exploration of different ways in which an identified or desired service-level provided by the in-use stocks can be reached. Connecting service levels to resources in this way is analogous to using the function provided by a product as the basis of the analysis as done in the *RNL* indicator, and which is also a foundational feature of LCA. In contrast, an inflow-driven approach takes its starting point at the inflows, which are used to calculate stocks and outflows.

In short, the type of results provided can either be relative or absolute resource quantifications, and could link resources to the services or functions these provide to the user.

4.5 Summary of comparison

The comparison of the two methods focuses on four aspects: the object of study, how time is represented, system boundaries, and the type of results (see Table 2). For the object of study, a distinction is made between the unit of analysis and the technical system considered. The unit of analysis of CE indicators is a single product, while dynamic MFA considers several product units of one or several product types. The technical system is not necessarily different, but depends on the purpose of the study. It covers the processes within the life cycle—the comprehensiveness of which depends on the indicator or, for dynamic MFA, the decision made by the analyst.

A key distinction between the methods relates to how time is represented. The temporal resolution of CE indicators include one time period that encompasses the entire life cycle, which means that no stocks are accumulated in the system. A number of CE indicators include a parameter describing product lifetimes, but indicators make no distinction between when in time resource flows occur. In contrast, dynamic MFA evaluates several time periods where resource inflows and outflows are connected using a lifetime function. This means that stocks and stock changes are quantified for each period. For CE indicators, the time window of the studied system spans the life cycle. In contrast, the time window of a system studied with dynamic MFA is decided by the analyst.

The other system boundaries considered in the comparison are spatial and organisational boundaries. For CE indicators, these span the geographical area and organisations where extraction, production, use, and end-of-life occur. With dynamic MFA, the spatial boundary is decided by the analyst and the organisational boundary is often not specified.

The last aspect concern the type of results provided. CE indicators primarily present results describing variations of resource use over the life cycle of a product, which are expressed relative to other flows over the life cycle. In contrast, dynamic MFA provides information about absolute quantities and timings of stocks and flows. Resources are connected to the functions these provide in five CE indicators, one of which is expressed per unit of product function. Dynamic MFA can connect resources to the services these provide by coupling in-use stocks to a certain service level.

Table 2. Summary of the comparison between CE indicators and dynamic MFA.

	CE indicators	**Dynamic MFA**
Object of study		
Unit of analysis	- One unit of one product type.	- Several units of one or several product types.
Technical system	- Processes within the life cycle, scope depends on the indicator.	- Processes within the life cycle, scope decided by the analyst and depends on the purpose of the study.
Representation of time:		
Temporal resolution	- One single time period (duration of the life cycle).	- Several consecutive time periods (one year time-steps).
Connection between time periods	- No, stationary—do not consider when flows occur.	- Yes, dynamic—considers when flows occur and stocks accumulate.
Product lifetime included	- Yes (six indicators), No (30 indicators).	- Yes, through a lifetime function.
Time window of study	- Non-defined, corresponds to the product life cycle.	- Defined, commonly decades.
Other system boundaries:		
Spatial	- Non-defined.	- Defined.
Organisational	- Non-defined.	- Defined or non-defined.
Type of results:	- Variations of resource use over the life cycle.	- Absolute quantities and timings of resource stocks and flows.
Absolute resource quantification	- Yes, 1 indicator.	- Yes.
Relative resource quantification	- Yes, all but one indicator.	- Yes.
Links resources to functions/services	- Yes, 5 indicators, one of which is expressed per provided function.	- Yes, if service-level is connected to in-use stocks.

5 Analysis

The purpose of this licentiate thesis is to contribute to knowledge about methods for evaluating how CE strategies could affect resources, particularly focusing on CE indicators and dynamic MFA. The methods were compared with regards to four overarching aspects in order to shed light on the methods differences and similarities, and to provide recommendations regarding their use and potential further development. The following sections analyse and discuss some of the implications of the comparison. First, a key difference between the methods concern how they model time. Thus, what this means for what the methods are capable of capturing is discussed. Second, the comparison pointed out that both methods can link the use of resources to the services or functions these provide to their user. The importance of this for a robust evaluation of resources is therefore discussed. Recommendations and implications for method use are then outlined, before pointing to limitations and avenues for further research.

5.1 Importance of how time is represented in resource evaluations

An inherent distinction between CE indicators and dynamic MFA concern how they represent and consider time. The real system analysed with CE indicators is represented with a single time period that spans the product life cycle. In contrast, dynamic MFA evaluates resources over multiple time periods which are modelled in a systems model. As a result, dynamic MFA is capable of quantifying flows and stocks and how these could develop over time. This enables an analysis of the availability of secondary resources over time. For instance, in article II, the reduction of primary material demand from implementing a battery reuse and recycling business model is initially limited, even with a highly efficient recycling system. This is due to the time delay before materials become available for recycling or batteries become available for reuse. Furthermore, whether many CE strategies could reduce primary resources depend on whether they displace the production of new products or primary materials. For instance, the effect on primary raw materials from reuse depends on whether the reused product displaces a new product (e.g. on a one-to-one basis), and whether the displaced product would have been manufactured by primary or secondary raw materials (Cooper & Gutowski, 2015). Similarly, whether something is reusable only matters if there is a demand for the reused product or component (Ghisellini et al., 2016). These developments are possible to examine with dynamic MFA due to its inclusion of the size and timings of resource stocks and flows. As an example, in article II the share of new batteries that are displaced from reusing batteries in the circular business model is examined. The displaced battery production is eventually limited by a lack of demand for reused batteries. Limitations of circular strategies due to a lack of demand have been explored with dynamic MFA elsewhere. For instance, Modaresi & Müller (2012) quantified the potential oversupply of secondary aluminium castings from end-of-life vehicles due to quality losses in the recycling process. Thus, it cannot be assumed in all situations that there is sufficient demand for secondary resources, e.g. when there is a decrease in quality. This it is important to consider when conducting assessments.

A CE indicator can provide a, more or less, detailed account of the resource flows over the life cycle, ensuring that resource flow changes in the life cycle can be captured. However, this perspective also assumes the economy can absorb the secondary products, components, or materials that become available. Whether primary resources are displaced is then either outside the scope or dealt with through allocation. For instance, the methodology in the *Material Circularity Indicator* inherently applies the 50/50 allocation approach and assumes that recycled material displaces primary material to 50%. Since the life cycle is represented as a single time unit, it does not account for whether the product contributes to stock growth, replacement or maintenance of a stock, or whether the stock is declining. As noted above, material demand can only partly be supplied from recycled sources if the stock is growing—even if the share of material circulated is very high at the level of single product. It is worth emphasising that while resource stocks are growing, the idea of a fully circular economy is an illusion (Haas et al., 2020; Korhonen et al., 2018). There is a risk that this perspective is lost in evaluations with CE indicators, since the wider context in which the product exists is outside the scope of the assessment.

Six CE indicators include lifetime parameters and thus reward extensions of product lifetimes, which is a key part of the CE goal of resource-life extensions (Blomsma & Brennan, 2017; Bocken et al., 2016). However, due to the life cycle perspective, they do not capture potential trade-offs between CE strategies over time. For instance, reuse and recycling cannot occur at the same time and are thus mutually exclusive at a specific point in time (article II). This could be a critical perspective for policy target setting, e.g. recycled content targets could create disincentives for prolonging the lifetime of products (Albertsen et al., 2021). In article I, the ability to evaluate use extensions was found to be constrained for some of the indicators in another respect. Namely, the choice of system boundary in some of the CE indicators was limited to one use-cycle of the product. For the second-hand laptop (case e, article I), the complete life cycle consists of two use-cycles: production and first use, and preparation for reuse and second use. For seven of the 31 indicators tested, only the second use-cycle of the laptop was then included in the assessment, excluding the production phase and the laptop shares considered unfit for reuse. The development of products that have several use-cycles, for instance in the form of cascading uses, could be an important means of extending resource life and are therefore important to be able to account for in assessments (Campbell-Johnston et al., 2020). In contrast, multiple use-cycles are suitable to evaluate with dynamic MFA since products can be quantified across cohorts and reuse phases over time (e.g. article II).

In dynamic MFA, product lifetimes are modelled with a lifetime function. Depending on the level of aggregation these can describe the lifetime dynamics of broadly defined product groups or end-use sectors, or be specific to different product types (Wang et al., 2018). Uncertainties are large since there are few empirical data on lifetimes, in particular when different product types are aggregated and described with one lifetime function (Lanau et al., 2019). Additionally, modelling products using a single lifetime function assumes that its components reach end-of-life at the same time as the product, which is not necessarily the case. To address this issue, a dynamic MFA modelling framework that considers the lifetime dynamics of products and components separately has recently been presented (Aguilar Lopez et al., 2022). They illustrate how considerations of both product and component lifetimes can be particularly useful for more detailed analyses of reuse and repair strategies.

The connection between inflows, stocks, and outflows over time make dynamic MFA appropriate for assessing different pathways of how a *transition* towards a more circular economy can play out, since current and possible future states are linked. In-use stocks, the adoption of circular business models, the diffusion of a technology, or available recycling infrastructure changes over time. Such time-dependent developments can be investigated with dynamic MFA—but are not suitable for assessing with stationary methods since these cannot distinguish between different time periods in the assessment.

5.2 Resources provide services and functions to their users

With both dynamic MFA and CE indicators, resource use can be linked to the services or functions these provide. In dynamic MFA this can be done by linking the in-use stocks to their provided services. For instance, a mobility service can be represented by a level of passenger-km that can be delivered by different vehicle types. The intensity of use could then be determined by the annual vehicle kilometrage and the number of people using the vehicles. Linking resources with services enables an exploration of how CE strategies could reduce resource use while maintaining or reaching a certain service level (Pauliuk & Müller, 2014). In the vehicle example, this could for instance be carried out though a reduction of vehicle size, increased ride-sharing, or car-sharing (Kamran et al., 2021; Pauliuk & Heeren, 2021). As outlined in section 4.4, stock-driven models derive the required stock from its service provision, and then calculate inflows and outflows. That is, the assumption is that stocks are driving the flows, and not the other way around. This presupposes that users are not primarily interested in the stocks themselves but in the services the stocks provide (D. Müller, 2006). Arguably, this approach focuses on human needs (provided by stocks), while the inflows represent the means to meet these needs (Stahel & Clift, 2015). Furthermore, saturation effects of stock build-up are likely to occur in the medium-term future for a range of materials in some regions, which stock-driven approaches are suitable to assess (Bleischwitz et al., 2018; Wiedenhofer et al., 2021). The focus on stocks stands in contrast to methods that are based on economic activity since these often describe flows (e.g. gross domestic product). An example of an approach focusing on flows is multi-regional EE-IO (Wiebe et al., 2019), which traces material flows, or other environmental extensions, along supply chains by connecting these with data on monetary flows.

The connection between stocks and services does not necessarily hold in all circumstances. It should for instance be critically questioned for consumables like food and fuels, where the flows provide the services (D. Müller, 2006). In a business model context, it might be appropriate to apply an inflow-driven approach if the inflows are the main sources of income, e.g. by integrating MFA with cost accounting (Baars et al., 2022). However, in product-service systems (e.g. the business model in article II), revenue streams can also be derived from providing access to a service (Linder & Williander, 2017), which could make a stock-driven approach suitable. Other means of, on a more fundamental level, quantifying the resource or energy demands associated with the services these provide have been presented—which instead focuses on the provisioning of universal human needs (Millward-Hopkins et al., 2020; O'Neill et al., 2018; Vogel et al., 2021). These studies link resource and energy use with a range of socio-economic factors, using a multi-variate regression approach, to determine the resource or energy requirements for reaching basic human needs on a global level. Explorations of how human needs can be met without transgressing sustainable levels of resource use are important from both an environmental and social-justice perspective, and particularly lends itself to circular economy discourses that focus on sufficiency (Calisto Friant et al., 2020; Wiedmann et al., 2020).

The inclusion of function in five of the CE indicators is similar to the stock-service perspective in dynamic MFA. Since the CE indicators consider a stationary system, the function is expressed over a certain unit of time, which is not the case in dynamic MFA because time is explicitly modelled. Four of the indicators benchmark the product function to an industry average and incorporate this into the indicator. These indicators will then only reward an above-average provision of function, but does not directly link the product to its function. One indicator, the *Relative Net Loss*, is expressed per functional unit—as a usage provided for a given lifetime. This was determined to be important for the outcome of the indicator during the testing in article I. It meant that the indicator could capture product changes like mass reductions while providing the same function, or lifetime extensions, which means more function is delivered to the user over the product's life cycle.

5.3 Recommendations and implications for method use

The choice of method ultimately depends on the intention for the assessment. Dynamic MFA quantifies stocks and flows of resources and how these could change over time when CE strategies are implemented. Thus, it provides insights about *when* return flows could become available, e.g. materials for recycling or products for reuse. In contrast, CE indicators focus on how various resource flows are altered over the product life cycle when CE strategies are implemented, without distinguishing when these occur. They provide information on how efficiently resources are used over the life cycle, often in relative terms since they are calculated from fractions between intermediary flows in the system. Thus, dynamic MFA is more suitable when knowledge on the timing and size of resource stocks and flows is required. For instance, analysing when secondary resources become available, how this matches resource demand at a certain point in time, or how a transition towards a more circular system over time could affect stocks and flows of resources. CE indicators are more suitable when analysing how CE strategies could affect resource flows at different stages in a product's life cycle, e.g. losses in production, share of components reused, or material recycled at end-of-life. However, they provide no information regarding the temporal developments of the system investigated.

As noted in article I, the difference between what is captured with CE indicators diverge significantly. The *multi-focus* indicators have a larger coverage of the life cycle and are therefore less likely to miss important resource flow changes. However, the aggregation of many aspects into a single value could make interpretations of the results difficult. In contrast, *single-focus* indicators are more straightforward to interpret and an assessment made with several of these could provide an understanding of changes in the real system and possible trade-offs. However, there is an inherent connection between applying a more wide-ranging indicator and the need for extensive data, which would have to be taken into account when choosing what indicator to use. The disparity of the multitude of CE indicators means it is critical to be aware of what they represent and leave out of the assessment. The flowchart tool and grouping presented in article I could be used for the purpose of choosing complementary indicators and clarifying what they capture.

The relative simplicity of the CE indicators could make them accessible and straightforward to use. Online tools exist for some indicators (Ellen MacArthur Foundation, 2023) or other types of documentation of their methodologies, which makes them readily available and easy to compute for practitioners or researchers. For MFA there are tools available, for instance the software STAN (Cencic & Rechberger, 2008), but no similar software solutions are currently available for dynamic MFA—which could be an obstacle to its further use. However, a number of open-source modelling frameworks have recently been presented that could make dynamic MFA more accessible to practitioners by harmonising the methodology and data structures (Aguilar Lopez et al., 2022; Pauliuk, Fishman, et al., 2021; Pauliuk & Heeren, 2020). Dynamic MFA has not been widely applied to evaluate resource use as at the company level but has instead primarily been focused on products or product groups on national or global levels. Some studies have investigated scenarios where a sector partially transitions to circular business models, e.g. to sharing-services or leasing solutions (Baars et al., 2021; Kamran et al., 2021; Sigüenza et al., 2021). Article II is the first, to its authors knowledge, to apply dynamic MFA to analyse the implementation of a circular business model. Studies at this level of analysis could be useful for exploring opportunities, limitations, and trade-offs between CE strategies at the level of a single company over longer time periods (Fu et al., 2021), which could be of interest to both companies and researchers.

6 Discussion

Different methods and tools can be described in relation to a vast number of characteristics and features (Baumann & Cowell, 1999; Finnveden & Moberg, 2005). The comparison presented here is not an exhaustive analysis of all differences and similarities between CE indicators and dynamic MFA. Instead, it is a way of synthesising the two articles by exploring and comparing the methods used within them. Previous comparisons of CE assessment methods have focused on the methods' capability of assessing CE strategies against the three dimensions of sustainability, as well as on their data requirements and the scope of the assessment method (Sassanelli et al., 2019; Walzberg et al., 2021). These studies do not include product-level CE indicators nor dynamic MFA in their analyses; the similarities and differences of which have been further clarified here. The need for a dynamic approach for assessing the implications of transitions to a more circular economy has also been proposed by Walzberg et al. (2021), but they instead suggest using System Dynamics and other methods from Complex Systems Science. Such methods have been suggested previously as having potential for integration with MFA to allow for dynamic assessments of CE strategies, e.g. by incorporating feedback mechanisms and non-linear system behaviours (Wiedenhofer et al., 2019). Investigating complementarities between such methods and dynamic MFA could potentially provide more robust dynamic models in the future.

6.1 Limitations

The analysis presented here could be expanded in a number of ways. There are additional methodological aspects that could affect the selection of the methods or the contexts in which they could be used, which were not included in this comparison. For instance, a comparison of the methods' data requirements and granularity (Walzberg et al., 2021) or the decision-making context in which they are used (Baumann & Cowell, 1999).

In article I, CE indicator results were compared to published LCA results presented in the studies that the cases were derived from. However, since LCA was not applied in the two articles in this licentiate thesis, the choice was made to not include LCA in the method comparison presented here. The inclusion of LCA, or other methods like EE-IO which have also been used for resource evaluations of the CE (Wiebe et al., 2019), could have highlighted other differences between the methods. For instance, Jerome (2022) recently compared CE indicators and LCA focusing on a number of modelling specifications and the types of results the methods provide.

The comparison and discussion was delimited to evaluations of resource use, leaving out aspects like energy use or environmental impacts. Dynamic MFA has, for instance, been coupled with data on energy, greenhouse gas emissions, or other environmental impacts to evaluate how CE strategies could affect these over time (Boldoczki et al., 2021; Liu et al., 2013; Vásquez et al., 2016). Expanding the comparison to include such aspects could provide additional insights into the differences between the methods and the types of information they can provide in a CE context. Furthermore, the work presented here has not addressed whether, or the extent to which, the methods are used by practitioners. For instance, Roos Lindgreen et al. (2022) investigated which assessment approaches that are implemented by a number of European companies engaged in CE practices. They found that only few approaches developed within academia are used in practice by the surveyed companies. Further research could study how methods are used in practice in companies and within policymaking, and explore ways in which practically useful tools and approaches can be developed and how their results can be used within decision-making processes.

6.2 Further work

Investigating ways that different methods can be combined in order to complement each other could be an important avenue for further research (Walzberg et al., 2021). For instance, Baars et al. (2022) review examples where MFA has been integrated with other methods to include, for instance, economic and social layers; or how it has been coupled with optimisation approaches (like computational general equilibrium models) in order to capture market responses connected to changes in the physical material system. For instance, while dynamic MFA can estimate the technical potential of product or material supply and demand, a market-based framework would be needed to incorporate price dynamics into the analysis (Zink et al., 2016). Such an approach could be used to analyse rebound effects from efficiency improvements related to the implementation of CE strategies (Skelton et al., 2020). Rebound effects could pose significant challenges to the extent to which CE strategies in fact reduce resource use and are therefore important to address in assessments (Figge & Thorpe, 2019). Baars et al. (2022) suggest that the economics field should be further integrated with MFA to improve its relevance to policy-making and decision-making at the company level. An example of the value of integrating economic conditions is provided by Krook et al. (2011). They quantify the stocks of copper in obsolete power grids in two Swedish cities and find that, although technically possible, it is not economically justified to recover these. Such an approach could be relevant in article II. For instance, the scenario where the circular business model is extended by using secondary batteries for stationary storage applications would only materialise if this is more profitable for the company than to recycle the materials back into production. Ultimately, this would depend on factors like the price of battery raw materials or the revenue streams from providing stationary energy storage. Integrating economic modelling with MFA could then be used to explore the financial viability of such solutions under different conditions, for instance analysing how subsidies or taxation policies could affect resource use (Lenglet et al., 2017).

Dynamic MFA has primarily been focused on global or national stocks and flows (Fu et al., 2021; E. Müller et al., 2014), while analyses at the company level or those that focus on circular business models are less common. Consequently, explorations of the resource dynamics of CE strategies at this level of analysis is limited. Thus, there are opportunities to further explore how various CE strategies or configurations of multiple strategies (Blomsma & Brennan, 2017), aided by circular business models, could impact resource use or environmental impacts over longer time periods. Such assessments could support companies in planning and designing business models, inform policymaking, or reveal more general trade-offs, limitations, or synergies between CE strategies. For instance, article II in this thesis illustrated how the displacement of battery production over time could be limited by company demand for secondary batteries, and quantified the potentials for business model expansion through extending battery-reuse for stationary storage applications. It also pointed to the tensions between reuse and recycling, and showed that the primary material savings from reuse were more substantive when recycling efficiencies are low. By applying case studies that cover different product characteristics and CE strategies—and by exploring how these could develop in different contexts, for instance under various speeds of technology development—more systematised knowledge could be generated about how circular solutions could affect resource use over time.

As an example, the case study in article II could be investigated further by analysing how additional CE strategies like technical-lifetime improvements, dematerialisation, or remanufacturing could affect resource use in the business model in the future. Furthermore, introducing new battery chemistries could affect the raw material demand and the battery lifetimes, or limit the reuse potential if different battery chemistries are incompatible (Ghalkhani & Habibi, 2023). Exploring such developments is of interest due to the expected increased competition for battery materials and production capacity in coming decades. It could also point to insights about the resource use implications of a transition towards more circular practices in a more generic sense.

7 Conclusions

The aim of this licentiate thesis was to contribute to knowledge about methods that evaluate how CE strategies could affect resource use by comparing product-level CE indicators and dynamic MFA. Building on the work presented in article I and II, an analytical framework was developed and applied to compare the two methods. Thus, the study has contributed towards more systematised knowledge regarding their differences and similarities, enabling insights regarding the type of information the methods provide and pointed to opportunities for method use.

CE indicators focus on a single product, while dynamic MFA focuses on several product units of one or several product types. A key distinction between the methods concerns how they model time. CE indicators model the life cycle as one temporal unit, and thus make no distinction between when resource flows occur within the system. As such, they evaluate the efficiency of resource use over the life cycle, but cannot be used to determine the temporal dimensions of resource flows, e.g. when secondary resources become available for additional use. It also means that no stocks are quantified since the resource flows associated with production, use, and disposal are considered simultaneously. Six indicators include a lifetime parameter and these are thereby able to reward an increase in product lifetimes.

Dynamic MFA evaluates several time periods where resource inflows and outflows are explicitly connected through a lifetime function. This enables an analysis of both stocks and flows of resources over time. It can be used to evaluate absolute quantities of resources within a chosen boundary and analyse the temporal dynamics of these, e.g. the age of the in-use stocks at a certain point in time or when secondary resource flows become available. This enables an analysis of the extent to which secondary resources can displace primary resources over time. With dynamic MFA it is also possible to examine potential limitations of CE strategies. For instance, how the lack of demand for secondary resources, e.g. reused products or recycled materials, could limit the resource reductions from CE strategy implementation. Since dynamic MFA links past, present and possible future developments, it is appropriate for analyses of different pathways of how transitions towards a more circular economy can occur. For instance, how changes today could affect the availability of secondary resources in the future, or when a certain CE strategy or policy need to be in place to reach a specific target.

Both methods can be used to link resources with the services or functions that these provide. Dynamic MFA does this by linking service provisions with in-use stock levels. In stock-driven modelling these can then be used as the model driver, exploring different means of reaching a certain service level. Five CE indicators link the product to its function, either through benchmarking this to an industry average or by expressing the results per function provided. The inclusion of function is important since it ensures that changes in total mass and increases in in-use lifetimes are captured by the indicator. Dynamic MFA has not been widely applied at the company level and only a few studies have focused on evaluating the temporal resource developments of circular business models. Thus, there are opportunities to further develop dynamic MFA models to evaluate the resource use implications of CE strategies over time at this level of analysis. This could aid companies in the assessment and planning of circular business models, and could reveal more general trade-offs, synergies, or limitations of such solutions.

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