ONTO-DESIDE

DELIVERABLE

D5.1 State of Knowledge Review

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Project summary

Circular economy aims at reducing value loss and avoiding waste, by circulating materials, components or product parts before they become waste. Today, lack of support for sharing data in a secure, quality assured, and automated way is one of the main obstacles that industry actors point to when creating new circular value networks. Together with using different terminologies and not having explicit definitions of the concepts that appear in data, this makes it very difficult to create new ecosystems of actors in Europe today. This project will address the core challenges of making decentralized data and information understandable and usable for humans as well as machines. The project will leverage open standards for semantic data interoperability in establishing a shared vocabulary (ontology network) for data documentation, and a decentralized digital platform that enables collaboration in a secure and privacy-preserving manner.

The project addresses a number of open research problems, including the development of ontologies that need to model a wide range of different materials and products, not only providing vertical interoperability but also horizontal interoperability, for cross-industry value networks. As well as transdisciplinary research on methods to find, analyse and assess new circular value chain configurations opened up by considering resource, information, value and energy flows as an integral part of the same complex system. Three industry use cases, from radically different industry domains, act as drivers for the research and development activities, as well as test beds and demonstrators for the cross-industry applicability of the results. The developed solutions will allow for automation of planning, management, and execution of circular value networks, at a European scale, and beyond. The project thereby supports acceleration of the digital and green transitions, automating the discovery and formation of new collaborations in the circular economy.

Project start date and duration

1st of June 2022, 36 months

Project consortium

No	Partner	Abbreviation	Country
1	Linköping University	LiU	Sweden
2	Interuniversitair Micro-Electronica Centrum	IMEC	Belgium
3	Concular Ug Haftungsbeschrankt	CON	Germany
4	+Impakt Luxembourg Sarl	POS	Luxembourg
5	Circularise Bv	CIRC	The Netherlands
6	Universitaet Hamburg	UHAM	Germany
7	Circular.Fashion Ug (Haftungsbeschrankt)	FAS	Germany
8	Lindner Group Kg	LIN	Germany
9	Ragn-Sells Recycling Ab	RS	Sweden
10	Texon Italia Srl	TEXON	Italy
11	Rare Earths Industry Association	REIA	Belgium

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0.7	2023-04-26	Mikael Lindecrantz	Deliverable internal reviewer	RS
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Table of Content

Abbreviations

CE	Circular Economy
WP	Work Package
UHAM	University of Hamburg
MFM	Multi-Flow-Metabolism
M	Month
T5	Task within work package 5 of Onto-DESIDE
D5	Deliverable within work package 5 of Onto-DESIDE
SLR	Systematic Literature Review
WoS	Web of Science
CDF	Circularity Design Framework
CM	Circular Metabolism
DT	Digital technology

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Summary

This deliverable presents the current state of knowledge on resource- (e.g., physical), energy-, information- and value-flows in the context of value chain design. It summarises existing research on design guidelines for a robust circular metabolism and lays the theoretical groundwork for WP5. The review results in two main outcomes. First, the Multi-Flow-Metabolism (MFM) is restructured. Based on the finding that information flows should not be regarded separately from material, energy, and value flows, but rather be included for each of the remaining flows individually, information flows are now included at the same level as infrastructure. The MFM now consists of material-, energy- and value flows each with respective information flows and enabling infrastructure. Second, a complementary framework to the MFM is developed: the Circularity Design Framework (CDF). The framework consists of three levels of principles: the circular metabolism factors, the circular enablers, and the implementation actions for material-, energy-, and value-flows. Five circular metabolism factors were identified and complemented with respective enablers. A first draft of implementation actions per flow is proposed, yet due to an existing lack of elaboration on material-, energy-, and value-flows in the literature, many gaps remain for the third level principles. The CDF will be used to transfer the underlying processes of a circular metabolism into design guidelines to be used within Onto-DESIDE and beyond. All principles are abstracted and formulated in a generic way based on the general finding that the focus should be shifted from including proposed solutions (e.g., interfirm collaboration) to system capabilities (e.g., 'the ability to work together'). This is done with the intention to be able to build further on the findings of this report with insights from practice and other academic disciplines in the next steps of WP5.

The review reveals important gaps within the literature: in the context of circular value chain design, (1) the gap with regards to holistic design of relevant flows was confirmed, validating this work, (2) the concept of value lacks a clear definition and should be regarded from a more holistic perspective; and (3) infrastructure is only scarcely covered. Further work is needed in these areas.

In the next steps of WP5, the abstracted principles will be used to connect to both practice and other research disciplines, e.g., Earth System Science and Complexity Science, to gain a more detailed understanding of each flow, refine existing principles and add missing ones. A more mature version of the framework will be used to advance the methodology as part of WP2 and will support the development of ontologies for circular value networks within WP3.

1 Introduction

Today society faces many severe environmental challenges, such as biodiversity loss, resource depletion and climate change. Many of these consequences can be traced back to the predominant linear economic system as the current 'take, make, use, dispose" paradigm has led to the consumption of resources beyond the regenerative capacity of our ecosystems[1,2]. It becomes apparent in society's excessive resource usage: at the moment, humanity uses the equivalent of 1.7 earths[3]. The number increases to 2.8 earths if everybody would live like an average EU resident. A radical shift in current production and consumption patterns and the organisation thereof is required[4]. Circular Economy (CE) is regarded as a promising alternative approach which simultaneously respects planetary boundaries and ensures economic and societal well-being[5,6]. However, despite its potential, the implementation of a CE is still at a nascent stage.

Amongst other barriers, the lack of support for sharing data in a secure, quality assured, and automated way is one of the main obstacles that industry actors point to when attempting to create new circular value networks. The use of different terminologies and the absence of consistent definitions makes it difficult to create new ecosystems of actors in Europe today. Onto-DESIDE will address these challenges by leveraging open standards for semantic data interoperability in establishing a shared vocabulary (ontology network) for data documentation, as well as a decentralized digital platform that enables collaboration in a secure and privacy-preserving manner. The project seeks to make decentralized data and information understandable and usable for humans as well as machines and will develop a data sharing platform for the digitalised CE. That said, the research required to bring Onto-DESIDE to a successful conclusion in the future is twofold. On the one hand, the transdisciplinary project requires research in the field of ontology modelling and for the development of an ontology-based data sharing platform. This work is conducted by work package (WP) 3 and 4 in close collaboration with WP2. On the other hand, given that Onto-DESIDE aims to contribute to the transformation of the European industry into a CE, further research, and knowledge creation regarding the design of circular value networks is required. Within Onto-DESIDE, these efforts are led by the team of the University of Hamburg (UHAM) and are concentrated in WP5. The report at hand is the first deliverable by WP5 and constitutes a state of knowledge review.

This introductory chapter continues with a short overview of the concept of CE and briefly presents the preceding research that builds the foundation for the work in Onto-DESIDE, namely the Multi-Flow-Metabolism (MFM) developed by Blomsma and colleagues[7]. This background section is followed by an overview of the tasks of WP5 before the objectives of this deliverable are described. Section 1 concludes with an outline of the remainder of the report.

1.1 Introduction to Circular Economy

In essence, Circular Economy is an umbrella concept that groups a wide variety of strategies, all for the purpose of value retention, reduction of value loss or alternative ways of value creation[1,7,8]. In its early stages, CE focused on waste and resource management strategies that aimed at extending product and material life through strategies such as recycling and remanufacturing[8]. While such circular strategies are, amongst others, still an integral part of the implementation of a CE, the understanding of a circular economy nowadays is more holistic, and challenges established assumptions. That is, CE encompasses a wide range of strategies that promote product, component and material conservation, efficiency, and productivity, e.g., recycling, reuse, maintenance, and manufacturing. Moreover, CE also involves strategies that look more directly at how value can be created or value loss reduced from a system point-of-view, e.g., for all stakeholders[7]. The concept of CE thus requires a rethinking of not only how resources flow through systems, but also who benefits and in what way, in order to realise the urgently required shift from the current linear economic model to a circular economic system[4,9]. This implies that more holistic and collaborative approaches are required[4,9].

As an alternative economic model which can support sustainable development efforts, CE has received attention from scholars, businesses, and policy makers[1,2,10]. This, for example, is reflected in the European Union's "Circular Economy Action Plan" (CEPA). As an important part of the European Green Deal, the CEPA "paves the way for a cleaner and more competitive Europe"[11] and thus aims to directly influence business and the way it operates. Onto-DESIDE contributes to the realisation of this action plan as the developed solutions will allow for the automation of planning, management, and execution of circular value networks, at a European scale, and beyond. However, despite the recognition of the potential of a (European) circular economy, the implementation of holistic circular value networks is still in its infancy, partly due to a lack of understanding of the complex system that circular networks represent and the ongoing interactions.

Previous research has shown that multiple flows play an integral part for a robust circular metabolism. That is: the industrial metabolism - the 'flows' that make up the lifeblood of systems such as economies - can be seen as consisting of resource- (e.g. physical), energy-, information- and value-flows[12–15]. It is when these flows are aligned and work collaboratively that metabolisms function harmoniously and within planetary boundaries. This occurs when value is provided to all relevant stakeholders by means of physical flows that respect the carrying capacity of the planet and which are facilitated by sustainable energy flows and supported by relevant information when needed. When large-scale metabolism changes happen such as when systems grow or advance to a new system state, these 4 flows - together with the accompanying infrastructure and technology - change in an integral manner to allow for new flow patterns to emerge[13–16].

Within CE the relevance of these flows is also acknowledged: see, for value flows, for example, work by Bocken et al.[17] or Pieroni et al.[18]; for information flows see the work by Kristoffersen and colleagues[19]; and see for energy flows the work by Cullen[20], Allwood and colleagues[21], or Bakker and colleagues[22]. So far, in CE, these 4 flows are studied with either an exclusive focus on one flow, or as a set of two, usually in relation to resources. However, Blomsma and colleagues[7] have recently shown that considerations regarding these 4 flows feature prominently and - crucially - *together* in circular oriented innovation. They are considered in relation to each other and designed together. For this reason, the Multi-Flow Metabolism (MFM) model was proposed to bring together these 4 flows (see Figure 1) and to emphasise their co-dependence in creating a sustainable circular metabolism.

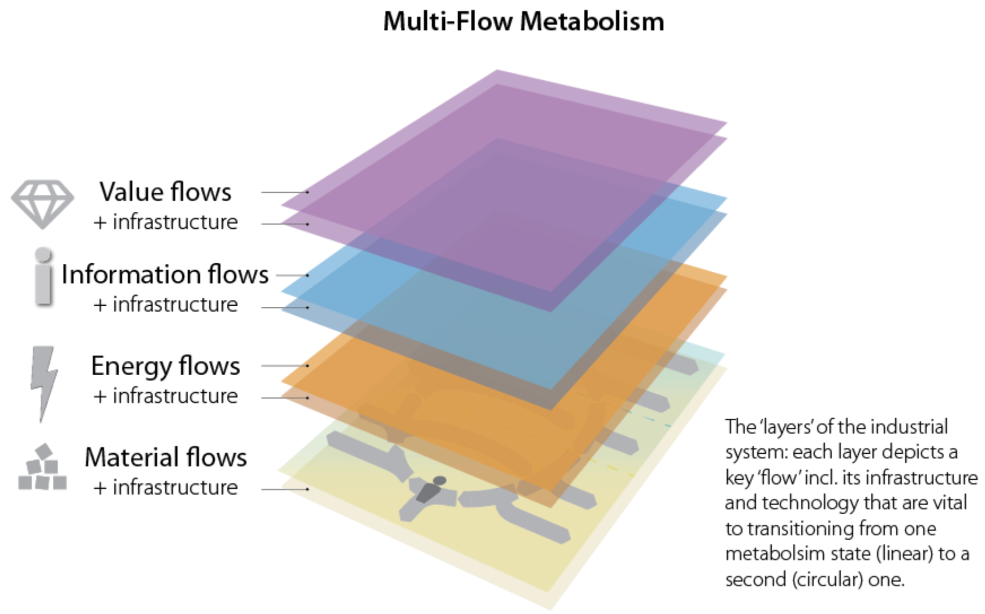

Figure 1 The Multi-Flow Metabolism by Blomsma et al. (2022)

However, at present, no comprehensive or authoritative guidance exists as to what a robust circular metabolism looks like – and how these 4 flows can be made into a coherent whole. Previous efforts to provide such guidance primarily take the form of circular design frameworks that propose a variety of design principles[2]. Examples of such frameworks are: Material Efficiency, which focuses primarily on the relationship between the production and circulation of materials and energy[21,23]; Cradle-to-Cradle which highlights three main principles: waste equals food, current solar income should be used, and diversity should be celebrated and diversity should be celebrated[24,25]; and the Blue Economy which proposes a list of 20+ such principles, including cascading through multiple kingdoms, replacing something with nothing, and generating multiple benefits[26]. These frameworks have several shortcomings. They a) do not systematically cover all fours flows, b) have limited scientific underpinning, and/ or they can c) vary wildly in the number and type of principles they propose, resulting in little trust in them. This means that there is a gap as to what guidance to adhere to when designing robust, sustainable, and circular metabolisms.

For change agents within business and other organisations this hinders the design and implementation of circular value chains, as it means that tools and methods to scan for and identify improvement opportunities that consider these 4 flows holistically are lacking. Considering both the pressing need to transition to more sustainable and circular industrial systems[27,28], as well as the current willingness and momentum to act[11,29]; this gap needs addressing urgently. Therefore, as part of the WP5 work within Onto-DESIDE, the MFM will be further developed into a method and tool that addresses this gap.

1.2 Tasks and Deliverables of Work Package 5

WP5, titled “Multi flow circular value network design & development method”, is led by UHAM. WP5 will (further) conceptualise, develop, validate, and implement tools and approaches that transform the MFM model into a method for the accelerated development of systemic circular solutions. The goal of this WP is to close the gap between idea and action for a CE and to turn the MFM into a strategic tool for use within Onto-DESIDE and also beyond. WP5 consists of three tasks (T5):

- T5.1: Review state of knowledge (M1-18) – lead: UHAM
- T5.2: Operationalisation & maturing (M10-30) - lead: UHAM, participants: CON, POS, CIRC, FAS, RS
- T5.3: Consolidation of method (M25-36) - lead: UHAM

and three deliverables:

- D5.1: State of knowledge review (amended to M11 with approval of EU project manager) – report
- D5.2 Multi flow circular value network design & development method – report
    - Version 1 (M24)
    - Version 2 (M36).

The three tasks build upon each other, yet they are also interrelated and overlap in time. The first task lays the foundation for the work within WP5, through an assessment of the current state of knowledge and practice around resource- (e.g. physical), energy-, information- and value-flows in the context of value chain design. A structured review draws from and consolidates knowledge and guidance for the design of these four flows from across different fields such as systems and complexity science, as well as the circular economy and supply chain fields. D5.1, the state of knowledge report at hand, summarises the findings of the initial state of knowledge review. The first task, however, continues until month (M) 18. In combination with the second task, T5.2, the report outcomes will be further developed and operationalised by turning them into a first version of guiding tools and methods. The developed methods will then be tested with the help of the industry partners and adjusted in an iterative approach. A description of these methods will be summarised in D5.2 Version 1. D5.2 also has a project milestone associated with it, i.e., Milestone 10: “First version of MFM methods”, which subsequently culminates in delivering T5.3: consolidation of methods (M36) The work done in T5.2 and T5.3 serve as the foundation for the development of part of the training materials within WP7. The corresponding task in WP7 is also led by UHAM. The final report, D5.2 Version 2, describes the finalised methods and tools, including a ‘how-to’ guide or manual aimed at a business audience.

In summary, WP5 develops a method and tool for the design of circular value networks with the end goal to produce a tool that supports the use-cases within Onto-DESIDE (WP6), but that can also serve a wide variety of other circular value chain efforts beyond the project. WP5 has a reciprocal relationship with the other WPs in that it also provides the frameworks and methods to study circular value networks within Onto-DESIDE. In turn, the methods brought forward in WP5 will be based on a sound theoretical foundation and the requirements of the industry cases (WP6), scoped by WP2. Where possible, WP5 outcomes will also be translated into ontological and further technical requirements for the construction of the Open Circularity platform by WP3 and WP4.

1.3 Deliverable Objectives

The current “State of Knowledge Review” report reviews and synthesises the current state of knowledge on resource- (e.g., physical), energy-, information- and value-flows in the context of value chain design. The objective of this report is to summarise existing research on design guidelines for a robust circular metabolism and lays the theoretical groundwork for WP5. The report will also serve as the foundation to connect to other research disciplines in a second step. At present, D5.1 primarily summarises the state of knowledge in the field of circular value chain design. Moving forward, these findings will be connected to additional disciplines such as Earth systems and complexity science in a transdisciplinary research approach to have a broad and deep understanding of metabolism changes. This will then be used to formulate design principles that are then used as input for the development of a first version of tools and methods in D5.2.

1.4 Input from other WPs so far

The methods developed within WP5 will be based on a combination of a scientific foundation and the requirements of the industry use cases in WP6. To ensure that the project treats (a set of) requirements from all three use cases, but that are general enough to also apply in other industry domains, WP2 set out to generalise the industry requirements. An initial set of requirements was summarised by WP2 and delivered in D2. 1 (M6). When the proposal for this project was designed, it was imagined that this would also provide input for WP5. However, the focus on individual user stories in D2.1 in service of the first software prototype resulted in the development of functional and non-functional requirements in which the value chain perspective was not developed to the degree that this provided meaningful input for WP5 yet. We aim to connect back to the findings of D2.1, i.e., the generalisation of the user stories, in our work following this deliverable.

The remainder of this report is structured in the following way. Section 2 explains the methodology applied for this state of knowledge review before the findings are presented in Section 3. Section 4 will then discuss the implications of these findings for the subsequent work of WP5 and other WPs where applicable.

2 Methodology

To fulfil the objective of this deliverable - to review the state of knowledge in the field - and to be able to utilise the findings in subsequent work, a four-step research methodology was applied (see Figure 2). A short overview of the entire process is presented first, before elaborating on each step in greater detail in the following subsections.

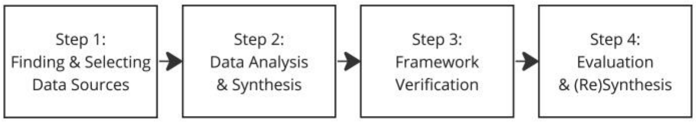

Figure 2 Research Methodology
(Own Illustration)

A Systematic Literature Review (SLR) was carried out to find what design guidelines exist for resource-, energy-, information- and value-flows in a CE. The first step of the SLR consisted of finding and selecting data sources. The findings were then analysed and synthesised in Step 2, resulting in the conceptualisation of a framework. To verify the results, in a third step, expert interviews were conducted. The framework was also presented to the consortium members where feedback was obtained in workshops. The last step, Step 4, involved the evaluation of the verification efforts and the subsequent resynthesis of the findings. Next, each step is explained in more detail.

2.1 Systematic Literature Review

SLRs rely on scientific principles and protocol-based procedures to ensure traceability, transparency and enable replicability[30]. As SLRs offer the opportunity to synthesise knowledge and to generate new insights, they are frequently used for state-of-the-art reviews[31,32]. Before any data can be collected, a protocol for the SLR must be established, which defines the specifications of the systematic review and enables other researchers to replicate the process. The following subsection outlines the research protocol for D5.1 before the data collection and classification is described.

2.1.1 SLR - Protocol for finding and selecting data sources

The protocol for the SLR of D5.1 is summarised in Table 1 below. The database accessible to the authors and therefore used for this review was Web of Science (WoS). WoS holds a high reputation and is considered one of the leading search engines for scientific research[33]. The “WoS Core Collection” was chosen as the specific data base. Additionally, only peer-reviewed articles that were written in English were selected. Considering that this SLR investigates what the current state-of-the-art is, the data range was limited to include only papers published within the past five years, i.e., from January 2018 until December 2022. This timeframe coincides with circular economy becoming an established theme within the academic literature. The keyword search was further limited to all fields pertaining to *topic*, which means that for a paper to appear in the search results the search terms had to be present in an article’s title, abstract, author keywords, or the keywords of the WoS . Further, a list of synonyms for each of the key words was established to aid comprehensiveness of the literature review, which were tested during a pilot phase. An overview of the synonyms chosen for each key word is provided in Appendix 1. As keywords were chosen: “CE”, “design principles”, “resources”, “energy”, “information”, and “value”.

Considering this SLR focuses specifically on how the four flows can be turned into a coherent whole, the search strings were designed to bring forward papers that capture the intersection of multiple flows. As one single search string combining “CE”, “design principles” and the four flows proved too narrow - resulting in a very limited number of papers - four individual search strings that each combine 3 flows were designed (see Table 1). A primary inclusion criterion was that the included papers discuss two or more flows in some detail, as opposed to articles that only mention the importance of other flows, e.g., in the abstract, but do not continue to consider these flows for the remainder of the paper. As such, papers were also included that offer detail on at least two of the three flows of that respective search string, and only minimal uptake of the third flow. The reason for this is the scarcity of papers that can be categorised as actually considering all three flows of the search string. This fact however does not come surprising given the research gap at hand.

Table 1 SLR Protocol for D5.1 (Adapted from Castro et al. (2022))

Research Protocol	Description
Data base	Web of Science (WoS Core Collection)
Search fields	Topic: title, abstract, author keywords, WoS keywords plus
Language	English
Data range	January 2018 until December 2022
Publication Type	Peer-reviewed articles
Search strings	Each search string includes synonyms for CE, Design Principles and three of the four flows: #1 CE *AND* Design Principles *AND* Material flows *AND* Energy flows *AND* Information flows #2 CE *AND* Design Principles *AND* Material flows *AND* Energy flows *AND* Value flows #3 CE *AND* Design Principles *AND* Material flows *AND* Value flows *AND* Information flows #4 CE *AND* Design Principles *AND* Energy flows *AND* Information flows *AND* Value flows
Selection criteria	Inclusion Criterion: Article discusses at least two of three flows of the respective search string in detail. A third flow must however be mentioned. Exclusion Criterion: Article only mentions multiple flows in the topic fields but only discusses one of the flows in detail.

2.1.2 SLR - Data collection and classification

The results of the four searches combined for a total of 1051 papers, including duplicates. All papers were analysed according to the following steps: review of 1) title and keywords, 2) abstract, 3) introduction and conclusion, and 4) full read, followed by the final decision for in- or exclusion.

During Step 1 and 2, a decision was also made regarding which search string a duplicate would be allocated to. Search string #4 represented a special case: 85% of all papers recorded, i.e., 110 out of 127, were duplicates. All 110 duplicates were assigned to one of the other search strings. The remaining 17 papers were eliminated during Step 1 or 2, resulting in the elimination of search string #4. After removal of duplicates from all search strings, a total of 832 papers made up the search result. Table 2 summarises the process of removing duplicates.

Table 2 Overview of data collection

Search String	**With Duplicity**	**After Removal of Duplicity**
#1 CE & DP & (MF, EF, IF)	281	220
#2 CE & DP & (MF, EF, VF)	344	275
#3 CE & DP & (MF, VF, IF)	426	337
#4 CE & DP & (EF, IF, VF)	127	*Search excluded.*
Total Number of Papers	1051	832

After step 4 a total of 51 papers remained that were selected for inclusion (see Appendix 2 for a list of all papers included). Table 3 shows the retention rates of each of the four steps. In this table each additional row describes the number of papers that have passed the previous step. For example, 220 papers were found for search #1. After the first step, i.e., review of title and abstract, 86 paper remained. After the abstract of these papers was reviewed, 44 articles remained. After the introduction and conclusion was read, only 26 papers remained and were read fully. Out of these 26, 22 were finally chosen. This low overall retention rate (22 out of 220 papers for search #1, 11 out of 275 papers for search #2, and 18 out of 337 papers for search #3) reinforces the knowledge gap identified in the above.

Table 3 SLR analysis process

Analysis Process	Search #1	Search #2	Search #3
Initial number of papers (adjusted for duplicates)	220	275	337
Remaining after Step 1: Title & Keywords	86	78	105
Remaining after Step 2: Abstract	44	23	43
Remaining after Step 3: Introduction & Conclusion	26	14	21
Remaining after Step 4: Full Read	22	11	18
		51	

2.2 SLR - Data Analysis and Synthesis

All 51 papers collected through the SLR were analysed and the findings synthesised into a framework. First, explicit design principles where extracted. Second, technologies and other enablers were also included, after their abstraction. The following describes this process in more detail.

2.2.1 Framework Development

The development of a framework “is a process of theorisation” [34] (p.57) in which similarities and patterns can be identified[35] from a multidisciplinary data set. A conceptual framework combines multiple interrelated concepts into one unit, thereby offering “a comprehensive understanding of a phenomenon or phenomena” (p.51)[34]. The development of a framework was therefore a logical step in summarising the findings of the SLR and to make them usable moving forward. First, all articles were read in an exploratory approach during which all relevant aspects were highlighted and saved that relate to the design of a CE and its four flows. During the initial reading, such aspects were selected in a generous way to remain open to a wide range of possible connections. Next, the data was organised by allocating each data point to either material, energy, value, or information flows.

The data analysis process resulted in the development of three categories. The first one consists of first order principles which are a high-level summary of the design principles applicable to all flows. As that, these principles indicate on a high-level what is required to design a circular metabolism and build the foundation for the development of our framework. Next, second-order principles were defined, called *circular enablers*, which give insight into how the first-order principles can be enabled. Lastly, all data that related specifically to the implementation of one of the flows was classified as a third-order principle. Third-order principles describe how second-order principles can be put into practice for each flow, respectively. The identification of the three-levels of principles resulted in the development of the Circularity Design Framework illustrated in Figure 3.

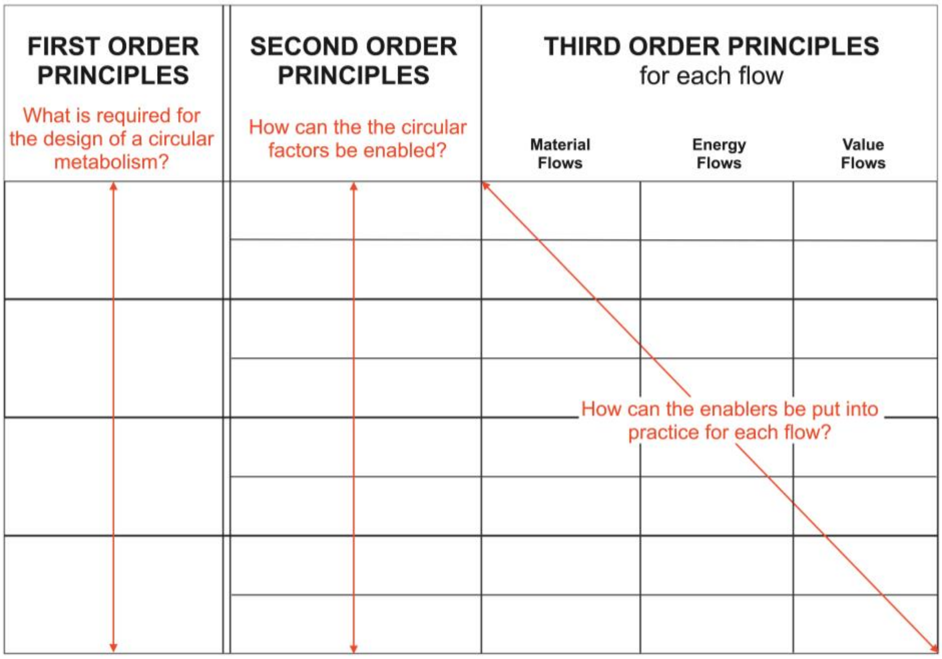

Figure 3 Structure of the Circularity Design Framework

The development of a framework has helped to organise the data in a structured way and will support the utilisation of the SLR findings. The identification of the three levels of principles provides insight into design requirements for a circular value network, by pointing towards the general requirements (factors) and elaborating on them with an increasing level of detail (enablers and factors).

2.2.2 Abstraction of Findings

Within the process of the data analysis, it was decided to abstract the findings. For example, collaboration among organisations[36] was identified as an enabler for the design of circular value networks and classified as a second order principle within the previous step of the data analysis. The capability underlying interfirm collaboration is the ability to 'work together for a shared goal'. The reason for the abstraction of the principles is two-fold. First, the literature review showed that the focus should be shifted from including proposed solutions (e.g., interfirm collaboration) to the system capabilities (e.g., 'the ability to work together'). Focusing on the capabilities provides the opportunity to identify additional approaches to facilitate a solution. In the case of interfirm collaboration this means, that working together for a shared goal can be facilitated through sharing infrastructure[37], but also through the use of digital technologies[38]. For example, digital platforms can facilitate the development of connections between multiple actors [39] and Blockchain technologies can support the open sharing of information between partners[40]. These examples demonstrate how the capabilities can be used to determine different ways to implement principles. In this manner, the abstraction makes the framework more technology agnostic and will resonate with practice more easily as their own solutions can find a place in it more easily. Second, given that the framework has been developed based on the findings of the SLR, which are dominated by research on circular value chains, this is reflected in the language used to formulate the principles so far. The abstraction process makes the framework sufficiently generic to be able to build further on these findings with insights from other academic disciplines in the next steps of WP5. Formulating all principles in this way can support the identification of similarities to and patterns studied in other disciplines. However, the business-centred formulations are preserved as alternative wording and allow for redundancy in the next development steps.

In sum: a thorough data analysis was conducted, the findings were synthesized, and the identified principles abstracted. The developed Circularity Design Framework (CDF) was then verified in a next step.

2.3 Verification

The CDF was developed through a protocol based SLR. To verify the framework, to collect additional data and to increase its validity, the framework was presented to experts in interviews. Additionally, the CDF was presented to the consortium members for feedback.

2.3.1 Expert Interviews

Expert interviews are an important step in ensuring research validity and offer the possibility to include additional input and close existing gaps[34]. The overall goal of the expert interviews was to verify the restructured MFM and the general structure of the framework. The CDF proposes principles for the design of circular value networks and offers first suggestions on how these can be put into practice for material-, energy-, value- and information flows. With that in mind, experts with a relevant background and expertise in the applicable research fields were selected. A total of 16 academic experts were approached out of which eight agreed to partake in our research. While this outcome is lower than anticipated, we still consider this a reasonable number as the interviews allowed us to verify our main outcomes, i.e., the restructuring of the MFM and the development of the CDF. We acknowledge that a greater number of interviews could have potentially helped to specify and uncover more implementation actions.

Table 4 gives an overview of the interviewees. Each interviewee is allocated a numerical ID by which the interviewee will be referred to within this report. It is indicated for which flow(s) the interviewee's expertise was considered helpful. In addition to the four flows of a circular metabolism, another area of expertise was added in the selection process: systems perspective. Given the purpose of the framework, expertise in the area of systems design is considered valuable. Interviewees were selected based on the indicated areas of expertise. The column on the far right provides an overview on each interviewee's research background and interests.

Table 4 Overview of interviewees

Interviewee ID	Material	Energy	Value	Information	Systems Design	Research Background
#1	X	X			X	Sustainable engineering, systems thinking, energy efficiency
#2	X	X			X	Resource and energy use in global supply networks, complex systems
#3				X	X	Systems thinking, complexity
#4			X		X	Circular Economy, sustainable design for CE
#5	X	X		X		Sustainable engineering, (urban) metabolism changes, CE
#6	X		X		X	Industrial eco-parks design, collaboration in circular ecosystems
#7			X			(Circular) Business ecosystems
#8	X		X		X	Strategy development for circular ecosystems

All interviews took place from February until April 2023. The interviewees were asked for a minimum of 60 minutes and maximum of 90 minutes. The interview durations differed based on availability of the interviewees, the shortest one being 55 minutes (#4) and the longest one lasting 110 minutes (#1). An interview protocol was developed in advance. The interviews started with an introduction of the UHAM project team and Onto-DESIDE project. The project's objectives, project partners and the general timeline were presented. Next, the role and objectives of UHAM within the project were outlined, leading to an overview of the interview purpose and scope. The second phase of the interviews was exploratory and asked for the interviewee's input on circular value network design based on their expertise. Open questions were posed to offer the interviewee the possibility to propose their opinion. Subsequently, the MFM and the restructured MFM were presented. Interviewees were asked to respond to the general idea of the MFM and to the transformation. The development of the CDF was presented next. At first, only the framework's purpose and the idea of the three levels of principles were explained and feedback requested. Then, the interview switched to an interactive activity facilitated on an online whiteboard. Interviewees were asked to respond to the first and second level principles before the conversation was directed to the third level principles. Interviewees were asked for their ideas on how to put the third order principles into practice for a particular flow. All interviews followed this protocol, adjusted for time constraints.

2.3.2 Presentation to Consortium Members

The Circularity Design Framework was presented to the Onto-DESIDE consortium in February 2023 at the in-person consortium meeting. In a first session, an update on the overall status of WP5 was given. During this presentation, the restructured MFM was presented, and the CDF was introduced. This included an outline of the background of the framework, an explanation and example regarding the abstraction process of the principles, an introduction to the three levels of principles and concluded with the overall vision for the framework within WP5. In a second session, an interactive workshop was conducted with the consortium partners. The goal of this session was to understand how the consortium views the proposed framework and its intended use.

All consortium members partaking in the consortium meeting, including on-site and online participants, were divided into three groups. The groups were put together with the intention to create a balanced mix of partners within each group so that industry and research partners would work together. Like the interviews, the workshop was also facilitated with the help of an online whiteboard space to allow all group members, including those partaking online. All three groups worked independently on the framework according to the approach outlined below while the facilitator switched between groups to address questions and to capture the ongoing conversation.

To make the framework more approachable to the partners, a hypothetical scenario was created. Partners were asked to imagine the following scenario: The group represented a team of a hypothetical firm that was hosting a booth at a CE industry conference. The group members were at the industry conference as experts since their firm was conducting a project on the implementation of circular solution for business. Representatives of a different company, that had no prior experience with circular economic practices, approached the experts (i.e., the respective Onto-DESIDE workshop group) and asked the three questions presented in Table 5, which also lists the corresponding principle level addressed.

Table 5 Overview of workshop questions and their corresponding principle level

Questions posed to the consortium group at hypothetical industry conference	CDF principle level addressed
1. Generally, what is required for a circular (economic) system to function?	First order principles (What is required for the design of a circular metabolism?)
2. You mentioned __ (requirement answered in question 1) ____, how do you enable this?	Second order principles (How can the requirements be enabled?)
3. How do you implement this specifically for your material, energy, and value flows? And what information is needed?	Third order principles (How can the enablers be put into practice for each flow?)

2.4 Evaluation

Following the conclusion of the interviews and the workshop, the findings of both verification formats were evaluated. In a first step, the general feedback on the approach taken by WP5 and the development of the CDF was summarised. Afterwards, the interview and workshop outputs were studied in a more detailed way by reviewing the outputs on the whiteboards and listening back to the recordings with the intention to confirm existing principles of the framework and to develop further ones. The finalisation of the CDF then allowed for a discussion on remaining gaps and the developed design principles for a circular metabolism.

To sum up: to review the state of knowledge on material-, energy-, information- and value flows for the design of circular metabolisms, a protocol-based literature review was conducted. The SLR produced 51 papers which were analysed, and the concepts synthesised into the Circularity Design Framework. Additional interviews and workshops with experts and the consortium members were conducted to verify and further develop (elements of) the developing framework. All findings are now presented in detail in the following section.

3 Findings

This section presents the descriptive and general findings of the SLR and the revised MFM. Next, the Circularity Design Framework is introduced. We continue by summarising the findings of the expert interviews and the consortium workshop and conclude with a detailed presentation of the framework and the circular metabolism factors, circular enablers, and implementation actions.

3.1 Systematic Literature Review

First, an overview of the descriptive findings is given and their relevance for this state of knowledge report explained. Second, the general results of the SLR are introduced.

3.1.1 Descriptive Findings

Based on the inclusion and exclusion criteria outlined in 2.1.1, 51 papers were selected. Table 6 provides an overview of the publications per journal and per year. The number of publications included increased continuously over the time frame considered. While only five articles published in 2018 were selected, the number tripled by the year 2022, from which 16 articles were included. This steady increase is in line with the increasing interest in CE and the development of circular economy as an area of academic study in recent years[41].

The selected articles were published in a total of 22 journals. Notably, 52% of all papers, i.e., 27 out of 51 articles, were published in just three journals: 12 in *Sustainability*, 10 in the *Journal of Cleaner Production*, and 5 in the journal of *Resources Conservation and Recycling*. Of the remaining journals, 7 journals are primarily concerned with the business perspective, including entrepreneurship, management, strategy development, innovation, and other aspects. Another 4 have a focus on research regarding energy, including the development of (sustainable and renewable) energy solutions and the management thereof. We note the concentration of the articles in three journals and note the absence of papers from domains such as systems and complexity science – the insights of which will have to be brought into this work via other means than the SLR.

Table 6 Publications per journal and year

Journal	2018	2019	2020	2021	2022	Total per Journal
Sustainability	2	2	3	2	3	12
Journal of Cleaner Production	1	1	2	4	2	10
Resources Conservation And Recycling	1		2	2		5
Business Strategy and the Environment (B)					3	3
Clean Technologies and Environmental Policy		1			1	2
Journal of Industrial Ecology		1	1			2
International Journal of Logistics Management (B)				1	1	2
Administrative Science (B)			1			1
Applied Sciences		1				1
Buildings			1			1
Business Strategy and Development				1		1
Energies (E)					1	1
Energy and Environment (E)				1		1
Environment, Development and Sustainability					1	1
Industrial Marketing Management (B)					1	1
International Journal of Production Economics					1	1
International Journal of Production Research)		1				1
Journal Of Industrial Integration and Management (B)	1					1
Management of Environmental Quality (B)				1		1
Renewable and Sustainable Energy Reviews (E)					1	1
Renewable Energy (E)				1		1
Technological Forecasting And Social Change					1	1
Total per year	5	7	10	13	16	51
General focus area of research journals: # of journals in category: (B) = Business perspective: 7; (E) = Energy: 4						

The observations with regards to the journal distribution are also reflected in the distribution of the WoS categories. These categories are allocated to an article on WoS based on the research area(s) that the paper addresses. One article may be assigned multiple categories at the same time. Therefore, the total record count of articles per category exceeds the total number of publications included. Table 7 shows the 10 most relevant categories for the 51 papers selected in the SLR based on record number. An additional nine categories were registered with one entry each, accounting for the remaining 17,64%.

Table 7 Overview of Top 10 Web of Science Categories

Web of Science Category	Record Count	Percentage of all 51 papers selected
Environmental Sciences	31	60,78%
Green Sustainable Science Technology	28	54,90%
Engineering Environmental	19	37,25%
Environmental Studies	17	33,33%
Management	8	15,86%
Business	6	11,76%
Energy Fuels	3	5,88%
Engineering Industrial	2	3,92%
Engineering Manufacturing	2	3,92%
Operations Research Management Science	2	3,92%

The top four WoS categories with the highest record count, i.e., *Environmental Sciences, Green Sustainable Science Technology, Engineering Environmental* and *Environmental Studies*, all relate to resources. Together with *Engineering Industrial* and *Engineering Manufacturing,* these categories relating to resources make up most of all record counts. The business perspective is the second most represented after resources with 16 combined record counts in the three categories of *Management, Business* and *Operations Research Management Science*. It is followed by the energy related category *Energy Fuels* with 3 entries.

To gain a more detailed understanding of the topics that are currently discussed in the literature on the design of circular value networks, the most cited papers were considered more carefully. To provide a comprehensive overview and to adjust for the varying time periods of different papers since publication, the Top 5 most cited papers per year were considered, see Appendix 3.

The three most cited papers overall were published by: (Geissdoerfer et al., 2018)[42] titled “Business models and supply chains for the circular economy”, (Bressanelli et al., 2018)[43] titled “Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies”, and (Upadhyay et al., 2021) [44] titled “Blockchain technology and the circular economy: Implications for sustainability and social responsibility”, with 385, 212, and 128 citations, respectively. The large number of citations for the work done by Geissdoerfer and colleagues suggests a strong interest by the research community for circular business models and supply chains. Considering the titles of the Top 5 most cited papers per year reveals additional topics. The use of Industry 4.0 technologies for the implementation of a CE, such as blockchain and big data analytics, is a trending topic, given that the use of these technologies is addressed in 12 of the 25 papers. The use of indicators and monitoring frameworks was an additional subject that received attention in numerous papers.

The following subsection presents the general findings of the SLR.

3.1.2 General Findings of the SLR: Restructuring the MFM

The exploratory reading of all 51 papers produced by the SLR resulted in the identification of five general findings, see Table 8:

Table 8 Overview of the general findings of the SLR

#1	Information flows should not be regarded separately from material, energy, and value flows.
#2	The data set showed a lack of elaboration of material, energy, and value flows.
#3	Infrastructure is not sufficiently covered in the data set.
#4	No clear definition of value flows for a CE exists.
#5	Rather than including solutions (e.g., DTs), their capabilities to satisfy a particular need should be considered.

All five observations (indicated in **bold**) and their implications for this state of knowledge review are now presented in greater detail.

#1 Restructuring the MFM

During the initial reading, the data was organised by allocating each data point to either material, energy, value, or information flows. The process of assigning the data to one of the flows revealed that many of the data points connected (at least partly) to information flows. Upon further examination, it was found that the data points previously classified as information also connect to at least one other flow. For example, Bianchini and colleagues[45] (p. 3) observe that "information, such as resource condition, location and availability" are helpful for the establishment of circular practices in which case the information required relates to material flows. That is: while such data points do relate to information flows, they all simultaneously also connect to either material, energy, or value flows. Bressanelli et al.[46] and Del Giudice et al. [47] find that information is required to effectively manage other flows of a CE thereby proposing that information is a means to facilitate a flow rather than an individual flow. This proposition is supported by other scholars as information is titled "an instrument" (p.3)[45] by some and "a support strategy for the circular economy" (p.6)[48] by others. Therefore, information flows will be regarded as part of material, energy, as well as value flows. This led to the decision to restructure the representation of the MFM and include information flows for each of the remaining flows individually, in the same manner as infrastructure. As a result, the MFM now consists of material-, energy- and value flows each with respective information flows and enabling infrastructure (Figure 4).

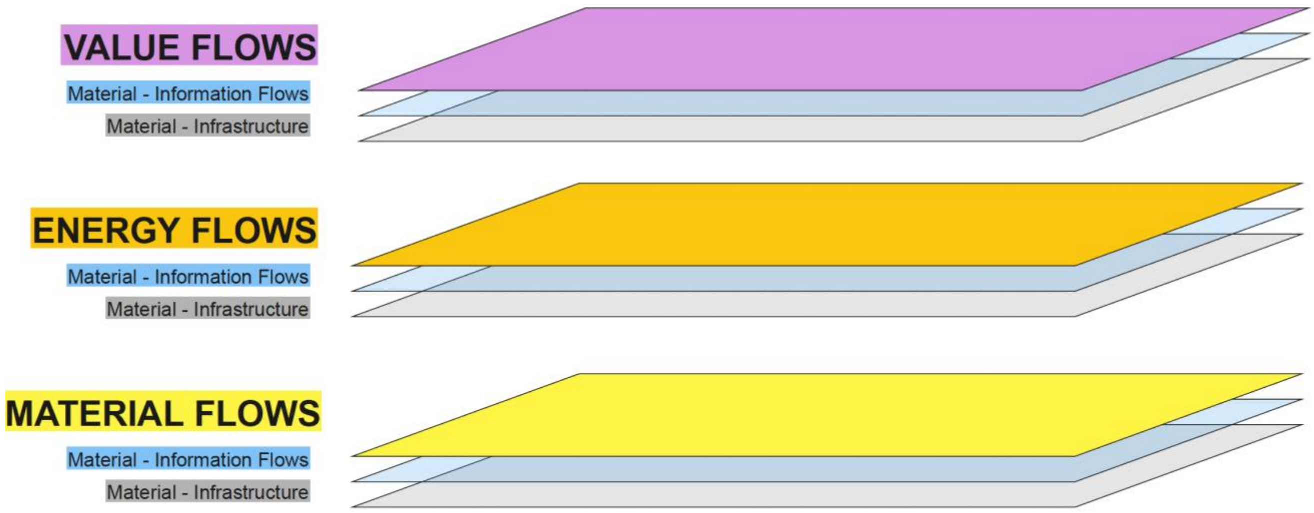

Figure 4 The restructured MFM

From this point forward, the restructured MFM serves as the high-level conceptual overview of a circular metabolism, replacing the original MFM depicted in Figure 1.

#2 Lacking elaboration of material, energy, and value flows

It also became evident that certain design propositions were relevant for any combination of flows. For example, collaboration was found to be important for closing material loops[36], for recovering energy[37], and for creating and capturing value[6]. Therefore, collaboration was specified as a first order principle, referring to a principle that is essential for the design of any combination of flows. They are followed by second-order principles which specify how the first order principles can be implemented. Both first and second order codes do not relate to only one flow specifically but instead propose general design guidelines, applicable to all flows. We developed such high-level categories due to an existing lack of elaboration on material-, energy-, and value-flows within the literature. This is important because it means that more specific design guidelines for each flow are lacking, and that the data cannot – at this point – be structured primarily according to the flows. Instead, the data of the SLR put forth many high-level principles relating to the design of circular value networks. Given the lack of data points specifically relating to the implementation of each flow, the framework was therefore designed around the first and second order principles. Wherever present in the data, these are complemented by third order principles which explain how the enablers can be put into practice for each flow respectively, but these are in need for further specifying as well as filling the gaps that remain.

#3 Insufficient consideration of infrastructure requirements

An important consideration in the design and implementation of a CE is infrastructure[7], as it sets the conditions for *what* flows can flow and *how* they can flow. Therefore, infrastructure is included in the MFM as a sublayer to each flow. However, even though enabling infrastructure is required in the context of circular value network design, it is not comprehensibly covered and only seldomly discussed in the literature. Being mindful of this, infrastructure was not explicitly considered in the search strings in an effort not to limit the search results. Out of the 51 papers analysed only seven even mention infrastructure[32,37,49–53]. The need to consider infrastructure and the possible development of new structures is supported by Siderius and Poldner[49] who point to the fact that the implementation of circular networks “requires (…) logistical and infrastructural investments” (p.6). The authors note that infrastructure developments will result in additional energy consumption. This observation is supported by Guedes et al.[32] who observe that it is important to determine the resources required to manage other (secondary) materials. Belaud et al.[53] consider the development of new infrastructure for the initiation of circular economic exchanges an issue. The low numbers of data points coming from only seven papers was insufficient to formulate design recommendations regarding infrastructure and calls for more research.

#4 Absence of a definition of value

The concept of value in the circular economy is lacking a clear and comprehensive definition. Even though value flows were discussed, no paper offered an actual definition of what value means in a circular value network. The most notable observation is that many scholars refer to the triple bottom line of sustainability when speaking about value, proposing that value flows consist of economic, environmental and social value[44,46,54,55]. This understanding of value possibly originates from the argument that the establishment of a CE is a way to achieve sustainable development[42]. While the existence of all three forms of value is often acknowledged, no detailed definitions are provided within the articles. Additionally, value is also often linked with (financial, environmental and social) performance[46,55,56]. As performance measurement is an important task for managing industrial systems, the development of indicators for a CE is essential[45]. Many financial and environmental performance indicators are put forward, yet the measurement of social performance proves more difficult and complex[45]. Example indicators include, but are not limited to: revenue generated, material costs saved, disposal costs saved and business growth generated for economic value; extraction of virgin materials, energy and resource efficiency, waste reduction for environmental value; and jobs created, improved working conditions, societal wellbeing and health and safety for social value[55,57]. Indicators can provide a general understanding of each type of value, yet indicators cannot replace thoroughly developed and comprehensive definitions as they are only “a small piece of an image of reality”[57] (p.9). In addition to considering the different impact dimensions of value, the concept should also be regarded from the perspective of different actors[58] as well as the different dimensions of value that exist. As the value of a good or a transaction can differ based on the respective stakeholder, different value perspectives should be acknowledged. This can entail such different views as one stakeholder looking at the economic value of a resource (e.g. value on the market), but another looking at the improvement or deterioration of material properties as this determines what applications the resource is suitable for. As a systematic approach to value is currently lacking, we conclude that the concept of value in the context of circular value chains requires further research.

#5 Inclusion of abstracted capabilities

Recent research attributes large potential to digital technologies (DTs) in supporting the transition from linear to circular economic practices[43]. The technologies considered promising for the so called Fourth Industrial revolution, also titled Industry 4.0[59], are, amongst others: Blockchain (see e.g. [56,59], Big Data and Big Data analytics (see e.g. [51,60]), Machine Learning (see e.g. [61]), Internet of Things (see e.g. [51,62,63]) and Digital Twins and Cloud Computing (see e.g. [62,63]). Advocates of the use of DTs for CE suggest that DTs can improve the implementation and management of a CE during each life cycle phase[43], by increasing value creation[38] and sustainability[63], and through the transformation of organisational structures[39]. For example, Blockchain can support the transparent collection and decentralized and traceable management of data[45], thereby creating economic value by reducing operating costs[56], environmental value through increased collaboration for resources and energy[37,51], and social value by protecting human rights along the supply chain[46]. Other scholars have raised scepticism and point to possible adverse and rebound effects[48]. For example, the concern is raised that, despite DTs undisputed potential for CE, it is not sufficiently understood how their use will affect value flows[46]. Additionally, the sustainability and environmental impacts of the use and production of DTs must be considered since, e.g., the processing of data requires large amounts of energy and often scarce virgin resources are necessary to develop and produce digital infrastructure[46,64]. Therefore, Bressanelli et al.[46] and Konietzko et al.[48] agree that DTs should be regarded as the “means through which the systemic design (is) enabled for a circular economy”[46] (p.9) rather than viewing the technologies as the end themselves[48] (p.6). This discussion results in an important learning: rather than focusing on solutions, the underlying ability to meet a particular need should be considered instead. For example, block chain technology is a frequently listed example that is attributed a high potential. But instead of including block chain technology as a solution to support the shift to a CE[44,56], we carefully looked at the new or desired capability that the use of block chain brings and included it as ‘the ability share information in a secure and traceable way’ and ‘the ability to make automated decisions’[44,64]. Following the same line of argument, we abstracted all findings. Table 9 lists a few examples to clarify the process.

Table 9 Examples of the abstraction process

Original wording based on the SLR	Abstracted principle
Stakeholder involvement	The capacity to integrate all (relevant) stakeholders throughout the (entire) process
Intra- and intercompany collaboration	The capacity to work together for a shared goal
Impact evaluation	The capacity to understand the effect of (a set of) actions (on the system)

In this manner the framework is made technology agnostic and sufficiently generic for both value chain practitioners to connect to with their own solutions as well as to be able to build further on these findings with insights from other academic disciplines in the next steps of WP5. Approaching the principles in such a detailed and differentiated way also provides the possibility to identify a supposed solution (e.g., a DT) as an enabler for other design requirements.

In sum, the exploratory reading resulted in five general findings. Particularly finding #1, the restructuring of the MFM, and finding #2, the lack of elaboration on material-, energy-, and value-flows, shaped the subsequent data analysis and framework development process. The CDF is now introduced in the following subsection.

3.1.3 Introduction to the Circularity Design Framework

This subsection introduces the CDF that was developed based on the process outlined in subsection 2.2. This introduction focuses on the structure and gives an overview of the factors to enable the reader to understand the essence of the framework. The circular metabolism factors and enablers are briefly presented, and their relation illustrated through an example. This builds the foundation for the next subsection, see 3.2, in which the general findings of the verification process are presented. The final framework is then presented in detail in subsection 3.3, combining the findings from the SLR, the interviews and the consortium workshop.

After the restructuring of the MFM, all information data points were reassigned to either material-, energy- or value-flows. The reorganisation of the data showed that several design guidelines were important for the design of any combinations of flows. For example: 8 papers considered it essential to switch from a single organisation perspective to a systems perspective that considers all stakeholders, processes from all life cycle phases of the value chain, and interrelationships to other system levels[9,36,46,47,50,58,65,66]. As this applies to all four flows – resources, energy, information, and value - having a holistic approach was defined as a first order principle. The established first-order principles are called *circular metabolism factors*; a factor being something “that influences the result of something”[67]. The circular metabolism factors, also simply referred to as factors within this report, answer to the question: what is required for the design of a circular metabolism? The factors are high-level guidelines that propose superordinate design considerations equally applicable to material, energy, and value flows.

The factors are followed by the second-order principles called *circular enablers*. Enablers are defined as something “that makes it possible for a particular thing to happen or be done”[68], the circular enablers answer to the question: How can the circular factors be enabled? The enablers provide more specific requirements for the realization of each factor. The enablers in turn are complemented by the *implementation actions*, the third-order principles. The implementation actions deliver specific suggestions how an enabler can be implemented for material, energy, and value flows. Information flows are included in the framework at the level of implementation actions, i.e., by outlining which information is required for the enablement of a factor. Figure 5 shows the circular factors and enablers of the CDF.

Circular metabolism factors	Circular Enablers	Material flows	Energy flows	Value flows
Holistic Approach >> The capacity to understand the system and its relations	Holistic system perspective >>The ability to understand interrelations between processes and actors in the system			
	Identification of all stakeholders >> The capacity to identify and consider all (relevant) system actors			
	Inclusion of all life cycle phases >> The capacity to consider processes throughout entire life cycle			
	Consideration of different system levels >> The capacity to understand interrelations with other systems (at different levels)			
Comprehensive Analysis >> The capacity to evaluate actions & processes	Extensive (possibility) scoping >> The capacity to scope (new) combinations of processes			
	Consideration of external factors & barriers >> The capacity to understand external factors and system barriers			
	Impact evaluation >> The capacity to understand the effect of (a set of) actions (on the system)			
Adaptation >> The capacity to adapt	Knowledge creation (& sharing) >> The capacity to acquire and share (new knowledge)			
	Innovation >> The capacity to develop new configurations			
Collaboration >> The capacity of actors to collaborate	(Intra &) Inter company collaboration >> The capacity to work together for a shared goal			
	Stakeholder involvement >> The capacity to integrate (relevant) actors throughout entire process			
Governance >> The capacity to manage the system	Effective management >> The capacity to coordinate processes and actors for the benefit of the system			
	Communication& trust >> The capacity to share information with actors in an effective and trustful way			

Figure 5 Overview of the Circularity Design Framework
(For the purpose of overview, the material, energy and value flows are omitted here.
See subsection 3.3 for more detail.)

The circular metabolism factors are located on the far-left side of the framework. The five factors are each complemented by the circular enablers in the adjacent column. The remaining three columns on the right hold the implementation actions for each flow. The implementation actions are not shown in Figure 5, instead they are presented in detail in subsection 3.3. After their identification, the findings were abstracted, as described in 2.2.2. The framework still holds both wordings (e.g., a handle for how it is (most commonly) referred to in the literature and a handle for the abstracted capacity) to allow readers from a variety of research communities and industries to understand the framework and the process.

The current version of the framework consists of five circular metabolism factors which are outlined below. The descriptions below only provide a summary of the factors and the respective enablers based on the SLR findings. They will be presented more thoroughly in 3.3.1 under consideration of the interview and workshop findings. To promote a thorough understanding of the CDF at this point, the presentation of the second factor includes presentation of one enabler together with its implementation actions. This serves as an example of the general framework structure. The entire framework (including references) can be found in Appendix 7. The abstracted circular metabolism factors are written in **bold** and their original wording (in parentheses) in the following.

The capacity to understand the system and its relations (Holistic Approach)

The first factor relates to the necessity to understand a system in its entirety and through that being able to approach the design of circular metabolisms holistically[46,48,58,66,69]. It is a strategic factor that influences the remaining four factors by predetermining the general perspective applied. In essence, this factor facilitates the boundary scoping of both the current (linear) system and the envisioned (circular) system. To gain a comprehensive understanding of a system, it is necessary to include all life cycle phases[50], identify all relevant stakeholders[9] and processes[66] throughout the life cycle and understand how such processes and the system itself interrelate with other processes and systems (at different levels)[65], including feedback loops or feedback mechanisms that may exist and that may manifest over time.

The capacity to evaluate actions and processes (Comprehensive Analysis)

The second factor is one of three operational factors. The system, its processes and opportunities scoped by the first factor need to be comprehensively analysed, through the capacity to evaluate actions and processes, in order to make informed decisions[40,52]. The processes identified and their respective materials, as well as the current and potential stakeholders must be examined carefully and new possibilities in the form of new material, process and stakeholder combinations extensively checked[52,58,69]. The opportunity scoping process must consider external factors and potential barriers as these can be decisive for the actual realisation of new circular opportunities[45,55]. The ability to understand the effect of (a set of) actions (on the system), and evaluating the impact of said actions, contributes significantly to the possibility to make informed decisions[31,45,69]. Impact evaluation concerns as much the assessment of potential strategies that have not been implemented yet as it relates to the evaluation of current or past actions. How the capacity to scope (new) combinations of processes can be implemented for material, energy and value flows is proposed by the respective implementation actions presented in Table 10 which serves as an example for the framework structure generally.

Table 10 Example of the three levels of principles in the CDF

Circular metabolism factor	**Circular Enabler**	**Materials: Implementation actions** The ability to:	**Energy: Implementation actions** The ability to:	**Value: Implementation actions** The ability to:
The ability to evaluate actions & processes [Comprehensive Analysis] [40,52]	The capacity to scope (new) combinations of processes [Possibility scoping]	• Understand the connection of the quality and quantity of flows • Analyse the feasibility of exchanges	• Identify energy demand of rebound effects • Forecast energy demand and supply	• Evaluate economic feasibility of material and energy flows • Identify activities for value capture, creation, and delivery

To scope (new) combinations of processes for material flows, the connection between the quality and quantity of flows must be understood, for example: it should be considered how one actor's material quantity and quality might affect those of other stakeholders (interviewee #1). For example, if an actor receives low quality resources from another actor which are used as production input, this could in turn have implications for the quality of production output. Additionally, the feasibility of these exchanges must be checked[47]. In the context of energy flows, possibility scoping should include the identification of rebound effects[49]. By forecasting energy demand and supply, new exchange opportunities can be identified[51]. Additionally, the economic feasibility of the proposed material and energy circular configurations should be evaluated[37]. Lastly, activities for value capture, value creation and value delivery must be defined[58]. More third order principles are described in subsection 3.3.2.

The capacity to adapt (Adaptation)

The third factor, also an operational one, captures the necessity of current (linear) systems and products to be adapted and future (circular) systems and products to remain adaptable[36,65,70]. As circularity increases, interdependencies and the system's complexity may increase as well[45]. To establish resilience and remain adaptable, it is important to acquire new knowledge and to share knowledge (where appropriate) with other actors of the system[6,38]. Knowledge management is closely correlated with the ability to develop new configurations. The design of new configurations or the improvement of existing system, processes or products is essential to solve current issues and overcome impediments[9,50].

The capacity of actors to collaborate (Collaboration)

The fourth and last operational factor for the successful design of circular networks is the capacity of actors to collaborate. Given the interconnectedness and possible interdependency in circular systems, collaboration constitutes an integral part in the design and implementation of a CE[49,53,58,71,72]. Collaboration is based on the capacity to work together for a shared goal which includes collaborative behaviour not just with external actors (intercompany collaboration) but also within an organisation (intracompany collaboration)[49,71]. Successful collaboration also includes the capacity to integrate (relevant) actors throughout the entire process[42,55,58]. A variety of stakeholders should be engaged throughout the entire product life. For example, engaging in conversations with target users during the design phase may help to better identify the need that a product satisfies which could in turn lead to new and innovate ways to meet this demand [58,71].

The capacity to manage the system (Governance)

The fifth factor, the capacity to manage the system, is an organisational factor. The above mentioned interconnectedness of actors and resources requires careful governance[31,73]. Effective management requires the ability to coordinate processes and actors for the benefit of the system[69,72,73]. Circular value networks bring together many different stakeholders which often belong to different groups (e.g., society, companies, and individual actors) and have different objectives and procedures[69]. This requires a form of governance that organises and coordinates for the benefit of the system. An important enabler is the capacity to interact and share information with actors in an effective and trusted way[37,49,54].

Subsection 3.1.3 has introduced the CDF and outlined the circular metabolism factors and circular enablers. The following section now presents the overall findings of the verification measures.

3.2 Verification Findings

The following section presents the results of the verification steps taken. Subsection 3.2.1 presents the findings from the expert interviews conducted, while workshop results are presented in 3.2.2. Both subsections only cover evaluation of the restructured MFM by the interviewees and workshop participants and present general feedback on the CDF. Detailed feedback to the factors and enablers as well as additions to the implementation actions are included in subsection 3.3.

3.2.1 Evaluation of Expert Interviews

A total of eight expert interviews were conducted to verify the findings of the SLR and obtain new insights. The interview objective was threefold: first, to get feedback on the MFM and its restructuring; second, to get feedback on the CDF, its structure and the factors and enablers; and third, to discuss implementation actions with the interviewee and possibly close remaining gaps. The first two objectives were successfully realised across all interviews. The third objective was only partially achieved. The reasons for this varied. In case of time constraints by the interviewee, the first two objectives were prioritised. Additionally, it proved difficult for some interviewees to define implementation actions due to their detailed character. In that case, implementation actions that had already been defined through the SLR were discussed. The actions that emerged out of the discussions were later added to the framework by the interviewer. The key learnings of the expert interviews are summarised in Table 11 (p. 2828) and will be presented in this subsection. For the remainder of the report, the interviewees are identified by their interview number, e.g., (#1).

The restructured MFM was positively received. All interviewees agreed with the step to include information flows as an integrated layer of the remaining flows and confirmed the context dependency of information: e.g., positioning it as part of the respective flows. Interviewee #2 also raised the point that information flows cannot be seen as individual flows in natural sciences which is a reasonable comment considering the resemblance of the MFM with natural metabolisms. A common topic of interest was the connection between the flows and the mechanisms that constitute each flow (#6, #7). It was proposed that the relationships between the flows should be indicated in the model once they have been discovered (#2, #4 and #5), e.g., by using arrows (#6, #7). An additional suggestion was to include the Circularity Compass, currently only included in material flows, in all flows (#5). This addition is supported by the remark that the direction of each flow is likely to differ (#6). The inclusion of infrastructure in the model was supported and regarded as important based on the impact infrastructure (development) has on a CE (#4): that is, infrastructure provides the affordance for *how* flows flow. Additionally, the importance of energy flows for circular systems was acknowledged (#2, #6), however, it was also noted that energy has not been considered sufficiently yet in the literature (#7).

The Circularity Design Framework also received positive feedback and opportunities to improve it were pointed out. To start, the value of such a framework for the useability of the findings and future implementation was recognised (#1, #6) and its structure considered to be in line with design thinking (#5). The cross-cutting structure of the factors and enablers across material, energy and value flows was perceived favourable for deriving design guidelines by interviewee #6. All currently listed circular metabolism factors were considered relevant (#1, #4; #6; #7; #8), yet a large overlap and interdependency between the enablers was recognised (#1), i.e., many enablers can support the realisation of multiple factors. This underlines the complexity and interrelatedness of the factors and enablers. In addition to factors and enablers, it was advised to consider contradictions and barriers more explicitly (#1). Based on the concern that the factors and enablers might change depending on the level of a system, it was advised to consider the influence of scale more explicitly in the design of the framework (#4). The interviewee emphasized that the principles for the design of a circular value network may differ whether they concern a meso level (e.g., an industrial park) or a macro level value network (e.g., a national economy). The factor time was also discussed and the need for timelines for the implementation was stressed (#7). Lastly, it was noted by interviewee #6 that a careful balance must be found between generalised factors and enablers and a case-by-case implementation, suggesting that the framework itself might need to remain adaptable for different contexts.

Table 11 Key learnings from expert interviews

Feedback on the restructured MFM • The restructuring of the MFM is logical. (all interviewees) • Information is an integral part of all flows. #6; #8 • The inclusion of information flows as an integrated part of the other flows is necessary because information (and energy) flows cannot be seen as individual flows in natural sciences. #2 • The model should be more detailed. #4 • The connection between the flows is of interest. #6, #7 Arrows might help to indicate their relationship. #7 • Flows do not necessarily follow the same direction (e.g., value flows other direction as material flows) #6 • Infrastructure development is an important factor for CE. #4 • Might be helpful to include the circularity compass on all levels of the MFM. #5 • Energy and information flows need to flow first to enable material flows. #6 • Actors play an important role in a system and thus should be considered carefully. #3
Feedback on the Circularity Design Framework • Framework will be helpful for the implementation of circular systems. #1; #6 • Framework in line with design thinking. #5 • All CM Factors are relevant. #1; #4; #6; #7; #8 • Cross-cutting of factors and enablers will be helpful. #6 • The enablers overlap and are interdependent. Numerous enablers are applicable for multiple factors. #1 • Challenges and barriers should be considered more carefully (in addition to the factors and enablers). #4 • Necessary to address contradictions within the framework explicitly and ensure consistency to enable usability of framework. and rebound effects. #1 • The system level that the framework addresses needs to be specified more explicitly. Different levels will also bring different factors and enablers. #4 • Stakeholders should be considered carefully in the framework. #4 • A balance between a generalised framework and case-by-case application needs to be considered. #6 • Timelines will play an important role. #4 Process thinking important. #7

Overall, the expert interviews resulted in positive general feedback for the results of the SLR and valuable suggestions for improvement.

3.2.2 Evaluation of Consortium Workshop

The workshop with consortium members took place as part of the in-person consortium meeting in February 2023. Given the limited time available for the presentation of the framework and for the workshop combined (about 1,5 hours total on both days), the primary objective was to obtain feedback from the consortium on the restructuring of the MFM and on the framework structure. These results and observations regarding the facilitation of the workshop are presented in this chapter.

The restructuring of the MFM was well received by the consortium members and all partners agreed. Strong support was received from members from WP3 in particular. During previous discussions, WP3 members raised the concern that they found it inconsistent to consider information flows separate from remaining flows. Their argument, that information is context dependent, and that information is essentially data from other flows (e.g., data on product quality, product location, etc.), was now confirmed by the SLR conducted within this report. Therefore, WP3 anticipates that the restructuring will benefit the cooperation of WP3 and WP5.

The Circularity Design Framework was also endorsed by the consortium. The presentation of the framework allowed the partners to understand its general value. Positive feedback was voiced by particularly by WP2 and WP3. For WP2, the framework can present a suitable means to facilitate discussions on the requirements of a circular value network with the use cases (WP6) and thus support the process of specifying the requirements. The framework can also help to transfer the knowledge created within WP5 into requirements for the development of ontologies (WP3), through providing further insight on the concepts necessary for the design and implementation of circular value networks. Members of WP3 noted that the abstraction of the principles will be helpful to support this process. The industry partners on the other hand found it harder to work with the abstracted principles. The members of WP6 understand the reasoning behind the abstraction and see the value it adds for the process of the project, nevertheless, the industry partners found it easier to work with the original wording of the principles. Considering that this framework will ultimately be used with practitioners, this is an important observation and points to the fact that the formulations in the framework will have to remain approachable for different types of audiences.

In addition to the feedback on the MFM and the framework, the workshop resulted in valuable learnings about the presentation of the MFM whilst it is being developed and when feedback is being sought. That is: greater emphasis must be placed on the introduction of the work to make it more accessible for the audience. Moving forward, more emphasis will be placed on the introduction of the kind of feedback sought and the type of audience, i.e., the participants' background will be considered more explicitly. Where possible, it will be helpful to conduct future workshops with each use case individually to be able to better address industry specifics and provide customized examples.

3.3 The Circularity Design Framework

This section combines the results from the SLR, expert interviews and the consortium workshop and presents the CDF in detail. The finalisation of the framework revealed that several gaps remain for the implementation actions. This is not entirely unexpected given that the articles included in the SLR were published in the wider business literature and thus do not present the level of detail required to define implementation actions for each flow. This observation is supported by the interviews, e.g., by interviewee #7 who mentioned that energy flows are not considered sufficiently within the literature, and interviewee #4 who noted that value creation and capturing is not yet well understood. This positions the circular metabolism factors and circular enablers as the primary outcome of the framework and suggests that further work is necessary to develop specific implementation actions for each flow. Therefore, the framework presentation is divided in two parts. Subsection 3.3.1 details the factors and enablers. The implementation actions are then summarised for each flow in subsection 3.3.2. A full version of the Circularity Design Framework, combining factors, enablers, and implementation actions, can be seen in Appendix 7.

3.3.1 Design Principles for Circular Metabolisms

In this subsection, all circular metabolisms factors will be written in **bold** and the circular enablers in *italic*. Arguments raised by interviewees are indicated by their respective number, e.g., (#1), and findings deducted from the consortium workshop by the group letter, e.g., (A). Table 12 (p. 34) provides a summary of all circular metabolism factors and enablers.

#1 The capacity to understand the system and its relations

The first factor is the capacity to understand the system and its relations, which concerns the necessity to understand the entire system and its relations. The importance of this strategic factor was confirmed within the interviews (#1, #2, #7), yet it was also cautioned that gaining a holistic understanding of a system is hard to realise in practice (#4). It is required that the focus is shifted away from a single organisation to an ecosystem perspective in which the system is regarded in its entirety[9,32,36,65], enabling *the capacity to understand interrelations (between processes and actors) in the system*. A systemic approach requires a long-term perspective[42,50] (#7) and the consideration of multiple perspectives[59] to avoid that the design of a circular network results in "burden shifting" instead of actually solving an issue[74] (p. 2), e.g., that environmental consequences are shifted to another geographic area or passed on to other generations. For that purpose, a wide perspective on problems must be applied[58], combing social and material systems[66].

To facilitate such a comprehensive perspective, *the capacity to identify and consider all (relevant) system actors* is essential[9]. The identification must move past immediate stakeholders, such as customers and shareholders, and also consider, e.g., society, future generations and the environment[9,66]. Since stakeholders are interdependent and more closely connected in circular systems[66], they must be considered holistically to understand the effect that actions of one actor have on others[75] and to comprehend the dynamics of a system[54].

Therefore, it is also important to *consider processes throughout the entire life cycle*. Given that each phase holds different potential to increase circularity and poses different challenges [53,76]. all life cycle stages must be examined, from resource extraction until end of product life, to determine all processes and stakeholders, and to be able to identify potentials for closing loops [61]. Particular attention should already be paid in the design phase as the opportunities to implement circular practices depend on decisions made during design[70].

Lastly, *the capacity to understand interrelations with other systems (at different levels)* is required for a holistic approach. Any circular value network is embedded within a larger (societal) system, making the consideration of different system levels and the connection to them an important strategic step (#2). The design of circular networks should therefore include processes and stakeholders across multiple levels, i.e., micro, meso and macro level[55,65]. Interviewee #5 proposed that an analysis should always be taken to the national level at the minimum to understand the applicable legislature and infrastructure conditions, e.g., the availability of take back systems and recycling facilities available. Despite acknowledging the importance of these enablers for a strategic approach to CE, interviewees #5 and #6 raise the concern of time intensity: instead of focusing on obtaining all information, it should be prioritised to collect only the information necessary for a comprehensive analysis.

#2 The capacity to evaluate actions & processes

Factor 2, the capacity to evaluate actions and processes, is an operational factor that directly intersects with factor 1. Based on the holistic system approach established through the strategic factor, actions and processes need to be evaluated to identify feasible circular practices and their impact must be evaluated. *The capacity to scope (new) combinations of processes* builds on a clear understanding of the current (linear) system based on which future scenarios can be designed[52,57,69] (#4; #8). To develop realistic opportunities for systemic transformations, the overall objectives of the system must be defined (A; B). Under consideration of the objectives, it can be evaluated if changes to the current system will be incremental or must be radical[52]. Different models should be compared[45], e.g., by simulating different future scenarios[62], and feasibility checks conducted[37]. The development of possible circular configurations should include different levels of circularity and take into account the overall system circularity level (#6; #8). For example: assuming the opportunity arises for an organisation to replace one of their materials to obtain a higher level of circularity, it should still be evaluated if that would increase or decrease the circularity level of the system. If the material replacement by one actor would result in the loss of material input for another one, this could decrease overall circularity. Therefore, the level of circularity should be considered carefully. The inclusion of all life cycle phases and all processes, established in factor 1, is important for the evaluation of actions and processes to account for possible rebound effects[50]. Understanding stakeholder dynamics helps to assess the conditions necessary for other actors to agree to a proposed circular solution[36] (B).

As part of understanding the feasibility of a proposition, *the capacity to understand system barriers and external factors* plays an important role. Internal as well as external system barriers must be assessed and other external factors, e.g., legislation and market forces, should be considered[45,49,58]. The necessity to carefully evaluate external influences and challenges was stressed by experts and workshop participants alike (#2; #4; #5; #6; B; C). Particularly national and international legislation and the influence of political institutions must be factored in carefully[45,55] (#5; #6; B).

Closely linked with the previous two enablers is *the capacity to understand the effect of (a set of) actions (on the system)*. Different results will be obtained depending on the strategy chosen and their impacts must be evaluated and compared[31,70]. Obtaining feedback is an essential part for the successful realisation of a circular value network and should be done regularly[69](#3). In addition to the implementation of verbal feedback structures (A; C), the use of indicators to measure performance and impact is emphasized by literature[57,70,74,77], interviewees (#1; #5; #6; #8) and consortium members (B; C). Indicators are a way to communicate [77], yet the interpretation of their results is crucial and must be regarded within the respective context to understand what it is that they actually show[57]. Generally, quantitative as well as qualitative indicators which measure outcomes in a comparable and replicable way are required [73,78]. However, more research is required for the development of indicators appropriate for a CE as current ones do not sufficiently cover the complexity of circular networks and do not reflect a systems perspective[74,75,77]. Even though numerous indicators should be used to capture the system's complexity, the establishment of aggregated indicators, which combine the results of various indicators into one score, should be considered to enable simple and effective communication[79]. For example, aggregated indicators could be included for different dimensions of value, e.g., financial, environmental, and social. Evaluation procedures should also consider the differing times required for circular strategies to create an impact as some effects may not materialise until a considerable period after implementation[31,37]. Impact evaluation should therefore be done in different intervals of time. It should also be evaluated how a set of strategies performs in relation to objectives defined for other system levels, e.g., the contribution towards the Sustainable development goals[78].

#3 The capacity to adapt

The capacity to adapt, being the third and an operational factor, addresses the requirement to adapt current systems and for newly configured system to remain adaptable. For that, *the capacity to acquire and share (new) knowledge* plays an important role as the level of knowledge required for circular systems exceeds that of linear value chains. Knowledge creation should include different forms of knowledge[80], i.e., explicit and tactic knowledge, and should be based on different sources[61], e.g., from practice and from science. The collection and analysis of data during all life cycle phases helps to construct a comprehensive understanding of the system[38,43], for example by developing knowledge on customer behaviour. An important aspect that promotes the creation of knowledge is the training and education of actors on circular practices and their value[47,54] (#7; #8) which can help to increase awareness and engagement, and to create a shared vision. This will in turn create favourable conditions for the capacity to develop new configurations (also factor 3)[36,55] and the capacity to scope (new) combinations of processes (factor 2)[39]. Knowledge sharing should be done in a simple and comprehensible way to enable its uptake by other actors[52](B). The visual presentation of knowledge is a form that can support this process[58]. So called blueprints also propose a way to share and make knowledge readily available, as they present typical processes and material configurations of a given sector[54]. This allows actors to consider information about certain industries without requiring the disclosure of confidential information by other organisations. Knowledge sharing routines and creative exchange sessions are also considered a promising way to encourage knowledge exchange and development since regular and open discussions can promote the transfer and development of specialized knowledge[36,69]. This could further lead to the establishment of knowledge networks[60]. Knowledge creation also encompasses the ability to analyse large amounts of data and generate precise, reliable and valuable observations from it[46,47].

Knowledge creation and exchange is a prerequisite for *the capacity to develop new configurations*, as innovation relies on the willingness to share information[36]. The development of new configurations for circular value networks should be based on a broader perspective than applied in linear systems[47], including technical as well as non-technical innovations (#5). Innovation should be considered for different aspects of circularity, ranging from eco system redesign to business model adaptation and product or process innovation[48]. While radical innovation and "non-usual initiatives" should be considered[9](p.3), innovation may also take place on a smaller scale[48]. Therefore, according to interviewee #4, identifying what exactly needs to be adapted is at the core of innovation. In order to both translate (new) knowledge into meaningful actions and to realise reconfigurations within a reasonable time frame, opportunities should be defined, evaluated and (re)adjusted in a dynamic approach[36]. Due to the increased interdependence and complexity in circular value networks, changes to the system may occur more frequently than in linear systems, requiring that evaluation and adjustments are made routinely[36], e.g. to be able to anticipate and react the failure of an actor in the system (#2).

#4 The capacity of actors to collaborate

Factor 4 is an operational factor that concerns the capacity of actors to collaborate and as that was described to “cover the people element” of circular metabolisms by interviewee #4. Scholars, the experts interviewed and groups of the consortium workshop all agree that collaboration is essential for the implementation of circular practices[49,71] (#4;#6; B; C). In comparison to linear value chains, the need for collaboration increases in circular networks[58], making intensive collaboration one of the core requirements for its design[48]. The capacity of actors to collaborate must be implemented through specific actions between actors, yet this capacity should also be taken into consideration in the context of other factors, e.g., for the capacity to adapt and the capacity to govern the system.

Collaboration is enabled through t*he capacity to work together for a shared goal*, which is required for many different purposes, from (product) design[49] to the recovery of materials[36] and value capturing[6] and needs to take place at many different system levels and across industries[57,60]. Such manifold collaboration is important as it increases the chances of scaling up[37]. While geographical proximity may be an advantage for collaboration in circular networks[53], it is not considered a prerequisite and opportunities to work together should be taken into consideration globally[37]. Even though a shared vision can support the ability to work together[60], it was pointed out by interviewee #6 that it is not a requirement. Instead, it is only required that the objectives of all parties align and do not contradict each other, but a shared overall objective is not a precondition (#6).

Collaboration needs to take place at inter and intrafirm level. While the literature points particularly to inter firm collaboration, for example along the supply chain[36], between competitors[49] and across industries[57], intrafirm collaboration was emphasized as an important enabler during the interviews. Interviewees pointed to the fact that many silos exist within organisations, i.e., a lack of communication and collaboration persists between departments or individuals (#4, #5). Additionally, the coordination and collaboration with top level management is an important form of intrafirm collaboration[72], as misalignment within the leadership team’s vision can impede the adaptation to a circular value network. Inter- and intrafirm collaboration also fosters innovation[6,36], an enabling condition for adaptation (factor 3). A reciprocal relationship can be identified for the ability to work together for a shared a goal with data exchange, that is: collaboration between firms can promote the exchange of data[81], yet sharing data also facilitates collaboration[80]. Visual communication is further suggested as a mean to share information in a simplified yet effective way[58]. This proposition is in line with the request raised by group B to communicate in a simple and intuitive way.

In addition to collaboration between and within organisations, the design of circular value networks requires that stakeholders are actively included and engaged in collaboration processes[42,47,71] throughout the entire life cycle[69]. Through *the capacity to integrate (relevant) stakeholders throughout the entire process*, stakeholder needs can be taken into consideration more explicitly and can support the (re)design of value chains[58]. According to interviewee #4, actively collaborating with stakeholders is also important to increase awareness, understanding and acceptance of circular practices to counteract existing inertia to change (away from linear value chains). One way to collaborate with stakeholders is to share information with the respective stakeholders on how one can and should contribute to the successful implementation of circular strategies, e.g., by forwarding information to users on production processes, and repair and recycle options[58].

#5 The capacity to manage the system

The fifth and organisational factor addresses the capacity to manage the system. The implementation of circular value networks combines a multitude of actors and processes and thus requires careful coordination to close loops[37,72]. *The capacity to coordinate processes and actors for the benefit of the systems* is an important enabler that includes the management of various resources, including human resources, financial resources and material resources[55,72], and different objectives and motivations[69]. A precondition for that is a shared understanding of the system[39], i.e., a general consensus regarding the system's boundaries. The establishment of a shared strategic vision is considered a favourable precondition[60] (#7; A), yet it is not regarded as an imperative prerequisite[69]. Management of the system should be conducted in a reliable and transparent manner[46,51,59], meaning that actors should be able to trust, comprehend and be able to trace decisions. One way to establish reliability are contracts (#2; #4; #5; #6; A; B). In practice, informal agreements also play an important role in the management of the system. Discussions with interviewee #4 and #6 showed that formal and informal agreements need to be balanced carefully. Interviewee #4 noted that informal agreements can impede an eventual scale up of a circular system (#4), while interviewee #5 reported that complicated and lengthy formal agreements can decrease the flexibility of actors to adapt to changes and currently hinder the redistribution of value within a system. The implementation of standards and common practices can further help to guide a system in a unified way, ensure compatibility and control quality[81] (B; C). Setting incentives to reach a goal was suggested by group C to motive and guide actors. The ability to collect and process large amounts of data can support system management by developing possible combinations of resources, actors and processes (and when necessary alternatives) which then supports decision-making processes[46,47].

Additionally, system governance requires *the capacity to interact and share information with actors in an effective and trustful way*. Trust is an important enabler for the management of a system[37,54,73](B; C) and a lack thereof is considered one of the biggest barriers for the design of circular value chains[37]. Reliable and transparent communication is equally important[37,73] and combined with trust builds the foundation for collaboration[37,53], knowledge sharing and innovation[36]. Communication should be facilitated in a transparent and traceable way[49]. Decentralised communication channels further increase the willingness to share information[44]. Communication efforts should not be focused only on collaborating companies but instead should include various stakeholders from all different life cycle phases (B; C). It should be done in an intuitive way appropriate for each stakeholder (B). This may be supported through the visualisation of information[19,58,81].

This subsection presented the circular metabolism factors and its respective enablers. We acknowledge that some enablers are likely to be applicable to other factors as well, and that interrelations between some factors also exist. These relationships must be regarded more closely in the further development of the CDF beyond this deliverable. All design guidelines outlined in this subsection are summarised in Table 12 which combines the circular metabolism factors, circular enablers and the clarifications described above. The alternative business-centred wording is included in [square brackets] and the factor categories are indicated in (parentheses).

Table 12 Design Guidelines of the Circularity Design Framework

Circular metabolism factors	Circular Enablers	Clarifications
The capacity to understand the system and its relations [Holistic Approach] *(Strategic factor)*	The capacity to understand interrelations between processes and actors in the system [Holistic system perspective]	• Comprehensive and long-term perspective • Required to avoid burden shifting
	The capacity to identify and consider all (relevant) system actors [Identification of all stakeholders]	• Inclusive approach to stakeholders past immediate stakeholders • Important to understand dynamics between stakeholders
	The capacity to consider processes throughout entire life cycle [Inclusion of all life cycle phases]	• Inclusion of all life cycle phases • Relevant to uncover circularity potential and possible challenges
	The capacity to understand interrelations with other systems (at different levels) [Consideration of different system levels]	• Consideration of different system levels: micro, meso and macro • System level important to scope general conditions (e.g., infrastructure and legislature)
The capacity to evaluate actions & processes [Comprehensive Analysis] *(Operational factor)*	The capacity to scope (new) combinations of processes [Possibility scoping]	• Builds on clear understanding of current (linear) system • Comparison of different future scenarios through feasibility checks
	The capacity to understand system barriers and external factors [Consideration of external factors and barriers]	• Assessment of internal and external barriers • Consideration of external factors (particularly legislation)
	The capacity to understand the effect of (a set of) actions (on the system) [Impact Evaluation]	• Evaluation of impacts • Implementation of feedback structures • Use of qualitative and quantitative indicators
The capacity to adapt [Adaptation] *(Operational factor)*	The capacity to acquire and share (new) knowledge [Knowledge creation (&sharing)]	• Consideration of different forms and sources of knowledge • Data collection throughout all life cycle phases • Analysis of large amounts of data • Training and education of system actors • Knowledge transfer in simple and intuitive way • Establishment of knowledge sharing routines and knowledge network
	The capacity to develop new configurations [Innovation]	• Innovation of different parts of the system • Based on broad perspective • Utilisation of dynamic and routine approach
The capacity of actors to collaborate [Collaboration] *(Operational factor)*	The capacity to work together for a shared goal [Intra- & intercompany collaboration]	• Necessary across different system levels and industries, and for many purposes • Includes inter- and intra-organisational collaboration • Alignment of objectives required • Not restricted by geographic proximity • Reciprocal relationship with data exchange
	The capacity to integrate (relevant) actors throughout entire process [Stakeholder involvement]	• Involvement of stakeholders during all life cycle phases • Important to increase awareness, understanding and acceptance of circular practices
The capacity to manage the system [Governance] *(Organisational factor)*	The capacity to coordinate processes and actors for the benefit of the system [Effective management]	• Effectively managing multiple types of resources • Reconciling varying objectives and motivations • Managing reliably and transparently • Utilisation of data for system management
	The capacity to interact and share information with actors in an effective and trustful way [Communication & trust]	• Trust as important perquisite • Communication in transparent, traceable and reliable manner

The following subsection now continues to present the findings of the CDF by presenting the implementation actions per flow.

3.3.2 Implementation Actions for Material, Energy and Value Flows

This subsection describes the implementation actions for each flow. The process of assigning the third order principles to the circular enablers showed that several gaps remain. It is considered a gap if no or only one implementation action could be identified. Figure 6 provides an overview of the CDF and its gaps, indicated through red circles on a scaled-down version of the CDF.

Circular metabolism factors	Circular Enablers	Implementation Actions		
		Material flows *The ability to:*	Energy flows *The ability to:*	Value flows *The ability to:*
The capacity to understand the system and its relations	The capacity to understand interrelations between processes and actors in the system		□ understand all parts of energy (i.e., exergy and anergy)	□ consider a diverse variety of value forms (incl. economic, environmental, and social)
	The capacity to identify and consider all (relevant) system actors	□ identify connections by analysing (large amounts of) supply chain data		
	The capacity to consider processes throughout entire life cycle	□ collect data along entire supply chain □ observe and track materials (in real time) throughout all life cycle phases	□ collect and analyse large amount of data fast □ visualise and simulate all processes	
	The capacity to understand interrelations with other systems (at different levels)	□ identify connections by analysing (large amounts of) supply chain data	□ understand carbon intensity and sustainability of energy sources □ visualise and simulate all processes	
The capacity to evaluate actions & processes	The capacity to scope (new) combinations of processes	□ analyse the feasibility of resource exchange (#5, #6) □ record material specifications and activities in central and standardised unit □ understand the connection of the quality and quantity of flows □ incorporate data from various sources □ visually capture processes	□ trace materials back to their origin to evaluate energy consumption □ identify energy requirements of rebound effects from material flows □ consider alternatives for achieving efficiency □ forecast energy demand and supply □ assess technical feasibility	□ evaluate the economic feasibility of material and energy strategies □ account for social and environmental externalities □ develop holistic value proposition □ identify activities for value creation, capture and delivery □ develop core objectives □ understand value created, value destroyed, value missed
	The capacity to understand system barriers and external factors		□ consider macro level energy infrastructure and legislature	
	The capacity to understand the effect of (a set of) actions (on the system)	□ understand success factors of exchanges □ measure and compare material flows □ evaluate direct and indirect effects	□ evaluate energy consumption and carbon emissions □ analyse large amount of data fast □ manage the dynamic and complexity of energy data □ measure rebound effects □ establish (prompt) feedback structures	□ measure economic, environmental and social value each □ combine all dimensions of value for a comprehensive evaluation □ assess value created, missed, destroyed
The capacity to adapt	The capacity to acquire and share (new) knowledge	□ track actions and decisions made by system actors	□ collect data during all life cycle phases □ incentivize the sharing of data	
	The capacity to develop new configurations	□ understand the qualities and characteristics of a material	□ collect and process dynamic and complex energy data quickly □ simulate processes to identify efficiency potential	□ define different types of value [60] □ understand underlying needs and wants
The capacity of actors to collaborate	The capacity to work together for a shared goal	□ share infrastructure (Hardware and software) □ align processes	□ share infrastructure (Hardware and software) □ collaborate for energy recovery □ bring together all energy sector stakeholders □ share information on energy demand and surplus	□ collaborate for value (co)creation, value transfer and value capture
	The capacity to integrate (relevant) actors throughout entire process	□ incentivize cooperation □ establish reciprocal information exchange	□ allow and encourage active engagement by consumers (i.e., prosumers) □ collect and provide consumption data during use phase	□ include stakeholders during identification of value □ integrate stakeholders in evaluation processes
The capacity to manage the system	The capacity to coordinate processes and actors for the benefit of the system	□ manage risk in case of exchange failure	□ manage energy exchanges decentralised □ make decisions automatically	□ establish shared vision and align objectives □ ensure that responsibilities and obligations are met
	The capacity to interact and share information with actors in an effective and trustful way	□ share information transparently and traceably □ standardise material information	□ share information transparently and traceably	□ verify value creation

Figure 6 The Circularity Design Framework and its remaining gaps

The category with the most remaining gaps is value flows with no or only one implementation actions identified for eight enablers. This may be attributed to the absence of a clear definition of value (general finding #3). Interviewee #3 also pointed out that the concept of value has only recently started to be explicitly incorporated in the study of industrial metabolisms. The interview experts agreed that value is a developing concept (#4; #5; #6; #7) which is often understood differently by each actor (#4). This disagreement impedes the identification of stakeholders, processes, and interrelations, which reflects in the gaps for factor 1 of value flows. Considering the existing gaps for each flow, the decision was made to present the third order principles per flow, instead of per enabler. Even though the factors and enablers are not consistently included in the following, they are written in *italic* (enablers) or mentioned with their respective number (factors) to provide structure to the descriptions of the flows whenever they are mentioned. Table 13 summarises the implementation actions per flow and can be used complementary to the CDF (Appendix 7).

Material flows

In the context of material flows, understanding the system and its relations means to gain a comprehensive understanding of the different types of materials, the processes and actors involved. The abilities to collect data on the material compositions and processes along the entire supply chain[44] and to observe and track materials (in real time)[45,46] relate to the necessity to gain knowledge of the flows involved in a system. The actions differ in that the first one relates to the general possibility to obtain data, regardless of whether this is done through data shared by other actors or through self-initiated data collection, while the second one concerns the ability to track materials, e.g., by using sensors, in real time. Together with the ability to identify connections by analysing (large amounts of) supply chain data[44], a thorough understanding of the material flows involved can be created. Analysing supply chain data helps to enable the necessary identification of actors and their respective processes in a system[46].

Data analysis also plays an important role for determining the feasibility of a possible resource exchange[47]. For that, information should be obtained, e.g., on the resource condition, location, availability, the processes and the required facilities[55](#5; #6). The collection of this information can be supported through the ability to record material specifications and track activities in a central and standardised unit, e.g., by using material passports[60]. Such record keeping combined with data analysis capabilities can also help to evaluate actions and processes, factor 2. For example, the information provided on material and processes can support the identification of process synergies[60]. Different data sources, such as company specific data as well as (open source) industry data, and different level of analysis should be included to understand correlations with other systems[82]. To enable a comprehensive analysis, it should be understood how one actor's material quantity and quality might affect those of other stakeholders (#1). The ability to visually present interactions can help to capture system dynamics and thus identify *opportunities for (new) combinations of processes*[32,37]. In order to *understand the effect of (a set of) actions (on the system)*, an enabler for factor 2, it is necessary to identify the success factors of a material exchange[55]. This includes the circumstances under which actors consider a transaction beneficial and will agree to it. Based on the success factors, new combinations of processes can be identified, and their performance evaluated. Measuring and comparing material flows is an important implementation action for evaluating performance that can be done through material indicators, e.g., on input and output flows[57]. The evaluation of direct and indirect effects of a resource exchange presents an additional action[83] that concerns the consideration of short and long response times, i.e., some effects can occur promptly while others may develop after an extended period of time.

To adapt, factor 3, knowledge must be acquired and when possible shared within a system. One way to generate knowledge about material flows is the ability to track actions and decisions made by actors during the use phase, which can help to create new learnings on specific material requirements[46]. To be able to develop new configurations, the qualities and characteristics of a material should be understood (#1; A), i.e., considering the need that the material satisfies within a product to identify alternatives. One way to *work together for a shared goal* is by sharing infrastructure[6,37], including hardware and software. Additionally, the alignment of processes[6](C), such as forward and reverse logistics, presents another form of collaboration. Incentivizing cooperation can support the *integration of actors throughout entire process*, e.g., by offering rewards to customers for returning their product[64]. Another opportunity to integrate stakeholders is the ability to establish a reciprocal information exchange[64], for example, that information is provided by customers (e.g., data on usage) to organisations who then in turn provide information on subsequent processes such as recycling or life extension opportunities. In addition to the general enablers outlined for factor 5, managing risk in case of exchange failure should be considered for material flows, e.g., through compensation agreements in case of the inability of one to party to meet responsibilities[37]. Additionally, the ability to standardise material information will help to communicate more effectively on material flows, e.g., by enabling the comparison of materials (C). Ensuring transparent and traceable information sharing is an important action for the design of circular material flows that can increase the willingness to share data and facilitate more comprehensive information exchanges[51].

Energy flows

In the context of energy flows, all parts of energy should be understood to make sense of the system's energy flows and its relations (factor 1), meaning that exergy, anergy and emergy should be considered[32,57]. Exergy is defined by Lütje and Wohlgemuth[57] as "the part of the total energy of a system that is actually usable and can do work, [while] anergy is the total opposite" (p. 7). The authors continue to explain that exergy is reduced throughout a material's life cycle and that additional energy is required for a system to remain at a specific level. The term emergy refers to "all of the past work performed by the environment, economy, and society in the entire process chain to generate a product or service (incl. all of the energy consumed in direct and indirect transformations)"[57] (p. 8). A differentiation between these concepts can enable a more comprehensive understanding of processes, actors, and system interrelations for energy flows. The collection and fast analysis of (large amounts of) energy data constitute important implementation actions for energy flows as such data can be particularly complex, dynamic and large in volume[45,63]. Similar to material flows, the ability to visualise and simulate processes can advance the analysis of energy flows and the identification of improvement options[46], by making complicated relations more comprehensible.

Tracing materials back to their origin helps to identify processes included in their earlier life cycle and thus to assess the total energy consumption[64]. Additionally, to evaluate possible new combinations of processes, the carbon intensity and sustainability of energy flows should be taken into consideration[51,82](#5). This means that the energy requirements for the provision of a type of energy should be reviewed (e.g., the infrastructure necessary to produce a type of energy). The study of energy flows should also include the identification of energy requirements from rebound effects resulting from material flows[49](#1). In the process of *scoping (new) energy configurations*, alternatives for achieving efficiency should be evaluated, e.g., increasing the energy efficiency of machines in comparison to that of production schedules[63]. Forecasting demand and supply serves as the preparation to plan energy production and identify possible synergies[51], which must then be checked for technical feasibility[37]. The consideration of macro level infrastructure, e.g., the availability of windmills, and legislature can support the act of *understanding system barriers and external factors* (#1). *To understand the effect of actions*, energy consumption and carbon emissions should be measured[49,83]. The results should then be evaluated, and conclusions drawn regarding (potentially) necessary adjustments. The establishment of (prompt) feedback structures can then facilitate dynamic adjustments[63].

Collecting energy data along the entire supply chain, including during the use phase, will foster the development of (new) knowledge[51,63]. The sharing of data by users but also by other organisations might require incentivisation[40]. In addition to its potential to facilitate collaboration for material flows, the ability to share infrastructure (in form of hardware and software) and to collaborate for energy recovery (e.g., through capturing excess heat) should both be regarded as implementation actions for energy flows as well[37]. Bringing together all energy sector stakeholders, including users and producers, is an important enabler for sharing information on energy demand and surplus so that the system energy demand, supply and excess can be calculated and redistributed[37,51,64]. Active engagement of users, particularly through the idea of prosumers, should be considered carefully for enabling the *integration of actors throughout entire process*[51]. The term prosumers "refers to the energy user who produces renewable energy in the home environment and shares the excess energy with the grid for commercial purposes"[51] (p. 188). Consequently, users could play a more active role in the design of circular energy flows. Consumption data should be collected during the use phase of a product to learn about user behaviour and to encourage more energy conscious behaviour by providing users with their consumption data[40](#7). Lastly, approaches *to coordinate processes and actors for the benefit of the system* include managing energy systems decentralised and enabling automated decision making on possible energy[51,56]. This can further be supported through the ability to share information transparently and traceably[51,56], which has also been identified for material flows.

Value flows

As previously outlined in the introduction of this subsection (p. 35), a large gap remains for the capacity to understand the system and its relations for value flows (factor 1). That said, the only implementation action identified for factor 1 is the ability to consider a diverse variety of forms of value. Scholars, experts and workshop groups alike point to the triple bottom line of sustainability for relevant dimensions of value, i.e., economic, environmental and social value[44,46,54,55] (#4; #5; #6; B; C). However, it was also noted that other perspectives of value should be considered, for example: what the value proposition of a circular strategy is for various stakeholders (e.g., the customer, business, or nature) and what the value would be for the product (#4).

Several implementation actions were identified for factor 2, evaluating actions and processes, and in particular for the implementation of *the capacity to scope (new) combinations of processes* and *understanding their effects*. A holistic value proposition should be developed that combines multiple and different forms of value[9,43,45] and accounts for social and environmental externalities[47]. Based on that, core objectives for the system and for actors should be established and activities for value creation, value capture and value delivery identified (per transaction and per stakeholder)[58] (#8). For that, the concepts of value created, value destroyed and value missed must be taken into consideration[58]. Measuring and assessing different types of value, e.g., through indicators, is essential to evaluate the economic, environmental, and social impact of circular strategies. While all three dimensions of value should be measured individually, it is also proposed to determine a combined evaluation score[51,57,66]. These efforts to assess value should also include an evaluation of the economic feasibility of material and energy strategies[37]. The impact analysis of set of circular strategies can then be used as the basis to adapt the value proposition when necessary.

To *develop (new) configurations*, relevant stakeholders and their respective values should be identified[38], i.e., value should be identified for customers, for producers and for the system. Understanding the underlying needs and wants that a product satisfies helps to develop more differentiated and detailed value propositions[38,83](B). *Working together for a shared goal* should include collaboration for value (co)creation, value transfer and value capture[6]. It is beneficial to *integrate relevant stakeholders* already in the value identification as well as in evaluation processes[9,54]. Establishing a shared vision[71] and aligning objectives of the system's stakeholders[50] can help to *coordinate processes and actors for the benefit of the system*. Additionally, formal and informal agreements help to ensure that responsibilities and obligations are met[37]. The verification of value is an important step to implement *effective and trusted interactions*, e.g., through the use of labels[83].

The implementation actions for material, energy and value flows presented above are summarised in Table 13. It is indicated with symbols which factor category an implementation action belongs to, i.e., strategic (●), operational (◇) or organisational (■). The specific factor allocation is indicated through the corresponding number of the factor (based on the order of the factors in the CDF). The information written in [square brackets] adds more detail to the implementation actions than included in the CDF.

Table 13 Implementation actions for material, energy and value flows

Factor categories: ● = strategic; ◇= operational; ■ = organisational
Factor allocation: numerical allocation based on the order of the factors in the CDF (1 = Factor 1; 2 = Factor 2; etc.)

Flow	Factor categories	Factor allocation	Implementation actions *The ability to:*
Material flows	●	1	Collect data along entire supply chain [on materials and processes]
	●	1	Observe and track materials (in real time) throughout all life cycle phases
	●	1	Identify multiple material flows at different system levels [to identify interrelations and scope possible (re)combinations]
	●	1	Identify connections by analysing (large amounts of) supply chain data [e.g., including data on processes and dynamics in other systems]
	◇	2	Record material specifications and activities in central and standardised unit [to summarise material and process information to enable information exchange]
	◇	2	Analyse the feasibility of resource exchanges [e.g., by processing supply chain data on resource condition, location, availability, facilities required, processes]
	◇	2	Incorporate data from various sources [e.g., company specific data; (open source) industry data]
	◇	2	Understand the connection of the quality and quantity of flows [i.e., how the quality and quantity of one actor affect the flows of another]
	◇	2	Visually capture processes [to reduce complexity and identify possible connections]
	◇	2	Understand success factors of transactions [i.e., under which circumstances actors consider a transaction beneficial and will agree to it]
	◇	2	Measure and compare material flows [e.g., measuring input and output flows; through the use of indicators]
	◇	2	Evaluate direct and indirect effects [i.e., considering short and long response times]
	◇	3	Track actions and decisions made by system actors [e.g., during use phase]
	◇	3	Understand the qualities and characteristics of a material [i.e., understanding which need a material satisfies (e.g., durability, water solubility) so that alternatives can be identified]
	◇	4	Share infrastructure [hardware and software]
	◇	4	Align processes [e.g., forward and reverse logistics]
	◇	4	Incentivize cooperation [e.g., with customers for product returns, with other actors to provide data]
	◇	4	Establish reciprocal information exchange [e.g., users provide usage data and company provides additional information to improve usage]
	■	5	Manage risk in case of exchange failure [e.g., find alternative material solutions to ensure system integrity]
	■	5	Share information transparently and traceably [to ensure confidentiality and increase willingness to share data]
	■	5	Standardise material information [to enable comparison of materials]
Energy flows	●	1	Understand all parts of energy [i.e., exergy and anergy]
	●	1	Collect data [on the energy flows required, incl. those related to materials flows and energy production]
	●	1	Visualise and simulate the energy flows for all processes [to understand the interrelations of these flows and be able to identify possible (new) configurations]
	●	1	Understand carbon intensity and sustainability of energy sources [e.g., energy requirements for the provision of a type of energy]
	●	1	Identify the energy requirements of material flow rebound effects
	◇	2	Consider alternatives for achieving efficiency [e.g., evaluating the energy efficiency of machine or of production schedule]
	◇	2	Forecast energy demand and supply [of the system and of organisations]
	◇	2	Assess technical feasibility [of envisioned energy transaction]
	◇	2	Consider macro level energy infrastructure and legislature [e.g., the availability of windmills or laws on renewable energy]
	◇	2	Trace materials back to their origin to evaluate total energy usage [during the entire life cycle]
	◇	2	Measure and evaluate energy consumption and carbon emissions
	◇	2	Analyse large amount of energy data fast [to manage large volumes of energy data]
	◇	2	Manage the dynamic and complexity of energy data
	◇	2	Establish prompt feedback structures [e.g., to allow for adjustments and efficiency increases]
	◇	2	Incentivize the sharing of data [e.g., from use phase or production processes, to be able to evaluate, improve and adapt processes]
	◇	3	Share infrastructure [hardware and software]
	◇	4	Collaborate for energy recovery [e.g., through capturing excess heat]
	◇	4	Bring together all energy sector stakeholders [e.g., producers and users]
	◇	4	Share information on energy demand and surplus [to enable efficient redistribution]
	◇	4	Allow and encourage active engagement by users [in form of prosumers]

	◇	4	Collect and provide consumption data during use phase [to incentivize users during use phase and enable learning effects for producers]
	◇	4	Manage energy exchanges decentralised
	■	5	Make automated decisions [on possible energy exchanges]
	■	5	Share information transparently and traceably [to ensure confidentiality and increase willingness to share data]
	■	5	Consider a diverse variety of value forms (incl. economic, environmental, and social)
Value flows	●	1	Develop holistic value proposition [to combine multiple and different types of value]
	◇	2	Account for social and environmental externalities
	◇	2	Establish core objectives [for the system and for individual actor]
	◇	2	Identify activities for value creation, capture, and delivery [per transaction and stakeholder]
	◇	2	Understand and assess value created, value destroyed, value missed [for the relevant stakeholder]
	◇	2	Assess the financial value of virgin and secondary resources
	◇	2	Measure economic, environmental, and social value each [e.g., through indicators]
	◇	2	Combine all dimensions of value for a comprehensive evaluation [e.g., by developing an aggregated score]
	◇	3	Define different types of value [e.g., for customer, for producer, for the system]
	◇	3	Understand underlying needs and wants [that are satisfied with a product or a transaction]
	◇	4	Collaborate for value (co)creation, value transfer and value capture
	◇	4	Include stakeholders during identification of value
	◇	4	Integrate stakeholders in evaluation processes
	■	5	Establish shared vision and align objectives [of the system]
	■	5	Ensure that responsibilities and obligations are met [e.g., through formal and informal agreements]
	■	5	Verify value creation [e.g., through use of certificates]

The implementation actions identified for each flow are a first attempt at identifying principles that facilitate the implementation of the circular enablers. The summary in Table 13 is not an exhaustive list and further work is necessary to refine existing implementation actions, to identify more and to close gaps.

Overall, section 3 presented the findings of the SLR, the expert interviews and the workshop with the project consortium. The conceptualisation of the findings resulted in the development of the Circularity Design Framework. All circular metabolism factors, circular enablers and their implementation actions were introduced. The following section now discusses the implications of the findings for Onto-DESIDE in the conclusion, section 4.

4 Conclusion and Implications

The objective of this deliverable was to review and synthesise the current state of knowledge on resource- (e.g., physical), energy-, information- and value-flows in the context of value chain design. A SLR was carried out, focusing on the intersection of multiple flows, to gain an understanding of how the four flows can be made into a coherent whole. The analysis produced several findings that lay the theoretical groundwork for WP5.

The literature review showed that information flows should not be regarded separately from material, energy, and value flows, but rather be included for each of the remaining flows individually, in the same manner as infrastructure. The MFM was restructured and now consists of material-, energy- and value flows each with respective information flows and enabling infrastructure. The review revealed that gaps remain regarding infrastructure and the concept of value in the context of circular value chain design. At present, infrastructure is only scarcely covered in the literature and a more comprehensive understanding of it is required. Additionally, the concept of value is missing a clear definition and should be regarded from a more holistic perspective, i.e., other dimensions than economic, environmental, and social value, as well as different stakeholder perspectives must be considered. Further development is necessary to establish a clear definition to be used within Onto-DESIDE.

Another outcome of the state of knowledge review is the Circularity Design Framework – a complementary framework to the MFM that consists of three levels of principles: the circular metabolism factors, the circular enablers, and the implementation actions for each flow. The framework development is still in its early stages, yet a mature version is planned to be used as the foundation for the development of a first version of tools and methods in D5.2. While the MFM is a high-level overview of a circular metabolism, the CDF is intended to be used for the transfer of the underlying processes of a circular metabolism into design guidelines. Based on the framework, a set of guiding questions will be formulated that can help to facilitate the design and implementation of circular value networks.

This review is grounded in the wider business literature in which, according to our analysis, the consideration of multiple flows is scarce. The data lacks elaboration on each flow, making the implementation actions proposed in this report a first draft. This positions the circular factors and enablers as the primary result of the framework development within this report. Since the articles included in this review only discuss a minimum of two flows in detail and offer at least minimal uptake of a third, the principles need to be cross-checked with other disciplines on large-scale metabolisms in which all flows are considered. Our analysis of the articles also confirmed the gap with regards to holistic design of relevant flows in the context of circular value chain design, thereby validating the WP5 work.

Another important learning of this report is the abstraction of the findings into principles. This approach made the framework more generic with the intention to enable value chain practitioners to connect with their own solutions and be able to build further on the findings of this report with insights from other academic disciplines in the next steps of WP5.

4.1 Implications for WP5

This deliverable summarises the state of knowledge on design guidelines for a robust circular metabolism, yet the task “Review state of knowledge” (T5.1) continues until M18 based on the findings of the report. The developed CDF serves as the foundation for WP5’s next steps. The abstracted principles will be used to connect to other research disciplines, e.g., Earth System Science and Complexity Science, to gain a more detailed understanding of each flow. It is expected that this will result in a more comprehensive list of implementation actions and an overall refinement of the CDF. The existing first and second order principles will also be reviewed with industry partners

(WP6) in an interactive session. This offers a chance to develop and test a different approach for the presentation and further development of our work, considering the learnings from the past workshop. As that, it promises to bring first insights for T5.2, the operationalisation and maturing of the MFM for a first set of tools. WP5 will also take measures to develop definition of value and to expand knowledge on infrastructure for circular value networks.

4.2 Implications for other WPS

The work within WP5 has implications, in particular, for the following WPs and the Onto-DESIDE project as a whole:

For WP2 - WP2 is responsible for the development of the ontological and technical project requirements, the integration of the three use cases, and for the generalisation of industry requirements. As part of its work, WP2 sets up the overall research and development methodology applied in the project (T2.2 led by UHAM). The results of the current deliverable have implications for this task in that the *circular metabolism factors*, the *circular enablers* and *implementation actions* may feed into the process to set these requirements as these set out design guidelines for a robust circular metabolism. In the next steps of both WP2 and WP5 this cross-fertilisation of these WPs will be further explored.

For WP3 - WP3 develops the ontology methodology (T3.1) in which it combines the requirements of industry partners and the methodological requirements for circular value networks brought forward by WP5. The developments of WP5 within the ongoing knowledge review task will thus serve as input for WP3 and the revised CDF will support the development of ontologies for circular value networks. This is accomplished through in this report and the ongoing state-of-the-art review having and continuing to articulate what is important to pay attention to for the design and operation of circular value networks. Which of the elements of the CDF and in what way they will be included in the WP3 ontology will be an ongoing collaborative effort between WP3 and WP5.

Onto-DESIDE project overall - In the first version of the ontology network architecture report (D3.1 submitted M9), WP3 found that value is a central concept that is currently unexplored in terms of its meaning and use for circular value networks. This finding coincides with the observations made in the current report. Within the Onto-DESIDE project as a whole, it will need to be decided how to address this issue as it impacts multiple WPs.

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Appendices

Appendix 1 Keyword Synonyms

Key word	WoS Search String	WoS Search Hits
Circular Economy	TS=("circula* econom*" OR "industrial ecology" OR "industr* ecosystem*" OR "closed*loop supply chain*")	11,335
Design Guideline	TS=("guideline*" OR " principle*" OR " recommendation*" OR "guidance" OR "framework*") * The word *design* was excluded from the search string as it resulted in a large increase of the search hits from other not applicable categories.	1,104,065
Resource	TS=("Resource*" OR "waste" OR "supply" OR "input" OR "product")	1,107,984
Energy	TS=("energy" OR "power" OR "electricity")	1,428,178
Information	TS=("information" OR "data" OR "knowledge" OR "communication")	3,257,956
Value	TS=("value" OR "benefit*" OR "advantage*" OR "profit*" OR "worth")	1,492,705

All searches were carried out under the following search criteria:

- WoS Core Collection
- Time Frame: 01.01.2018 until 31.12.2022
- English Only
- Articles Only

Additional synonyms were checked but the decision to exclude them as they increased the number of search hits significantly with articles from unrelated WoS categories.

Appendix 2 List of papers included from the SLR

Aarikka-Stenroos et al., 2022	Konietzko et al., 2020
Aguiar et al., 2022	Kosmol et al., 2021
Ávila-Gutiérrez et al., 2020	Kouhizadeh et al., 2019
Baldassarre et al., 2019	Kouhizadeh et al., 2022
Belaud et al., 2019	Laurenti et al., 2018
Bianchini et al., 2019	Liu et al., 2022
Brändström & Saidani, 2022	Luoma et al., 2022
Bressanelli et al., 2018	Lütje & Wohlgemuth, 2020
Bressanelli et al., 2022	Ma et al., 2020
Brown et al., 2021	Mendoza et al., 2022
Castro et al., 2022	Núñez-Cacho Utrilla et al., 2020
Cervo et al., 2019	Nuss et al., 2021
Çetin et al., 2021	Pauliuk & Heeren, 2020
Del Giudice et al., 2020	Prioux et al., 2022
Dey et al., 2022	Puglieri et al., 2022
Geissdoerfer et al., 2018	Pyakurel & Wright, 2021
Ghali & Frayret, 2019	Ranta et al., 2021
Guedes et al., 2018	Rohde-Lütje & Wohlgemuth, 2020
Howard et al., 2019	Scheel & Bello, 2022
Jacobi et al., 2018	Siderius & Poldner, 2021
Juszczyk & Shahzad, 2022	Upadhyay et al., 2021
Kambanou & Sakao, 2020	Vimal et al., 2022
Kardung et al., 2021	Yadav et al., 2020
A. A. Khan & Abonyi, 2022	Yildizbasi, 2021
S. A. R. Khan et al., 2021	Zhang et al., 2020
Köhler et al., 2022	

Appendix 3 Top 5 most cited articles by publication year

Publication Year	Publication Title and Author(s)	Number of Citations
2018	Business models and supply chains for the circular economy (Geissdoerfer et al., 2018)	385
	Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies (Bressanelli et al., 2018)	212
	Providing an economy-wide monitoring framework for the circular economy in Austria: Status quo and challenges (Jacobi et al., 2018)	49
	The Socio-Economic Embeddedness of the Circular Economy: An Integrative Framework (Laurenti et al., 2018)	26
	Bibliometric and Systemic Analysis on Material Flow Mapping and Industrial Ecosystems (Guedes et al., 2018)	4
2019	Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating Circular Economy and Industrial Ecology perspectives (Baldassarre et al., 2019)	116
	At the Nexus of Blockchain Technology, the Circular Economy, and Product Deletion (Kouhizadeh et al., 2019)	86
	The regenerative supply chain: a framework for developing circular economy indicators (Howard et al., 2019)	78
	Overcoming the Main Barriers of Circular Economy Implementation through a New Visualization Tool for Circular Business Models (Bianchini et al., 2019)	54
	A circular economy and industrial ecology toolbox for developing an eco-industrial park: perspectives from French policy (Belaud et al., 2019)	24
2020	Blockchain-based life cycle assessment: An implementation framework and system architecture (Zhang et al., 2020)	105
	Supply chain management in the era of circular economy: the moderating effect of big data (Del Giudice et al., 2020)	95
	Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries (Ma et al., 2020)	71
	A Tool to Analyze, Ideate and Develop Circular Innovation Ecosystems (Konietzko et al., 2020)	55
	Exploring indicators of circular economy adoption framework through a hybrid decision support approach (Yadav et al., 2020)	33
2021	Blockchain technology and the circular economy: Implications for sustainability and social responsibility (Upadhyay et al., 2021)	128
	Digital technologies catalyzing business model innovation for circular economy—Multiple case study (Ranta et al., 2021)	97
	Development of the Circular Bioeconomy: Drivers and Indicators (Kardung et al., 2021)	83
	Blockchain and renewable energy: Integration challenges in circular economy era (Yildizbasi, 2021)	36
	Digital technology and circular economy practices: An strategy to improve organizational performance (Khan et al., 2021)	31
2022	A framework of digital technologies for the circular economy: Digital functions and mechanisms (Liu et al., 2022)	26
	The rebound effect of circular economy: Definitions, mechanisms, and a research agenda (Castro et al., 2022)	20
	Adoption of circular economy practices in small and medium-sized enterprises: Evidence from Europe (Dey et al., 2022)	11
	Towards a collaboration framework for circular economy: The role of dynamic capabilities and open innovation (Köhler et al., 2022)	8
	Towards the Smart Circular Economy Paradigm: A Definition, Conceptualization, and Research Agenda (Bressanelli et al., 2022)	6
	Highlighted in green = papers relating to digital technologies Highlighted in dark green = papers relating to monitoring activities	

Appendix 4 Summary of detailed interview findings

Learnings for each circular factor

CM Factor 1: Holistic Approach

- Big overlap between CM Factor 1 & 2. #1
- It is a very important factor but it is very hard to actually fully understand a system in reality. #1, #4, #7
- Important to consider that circular value networks are also embedded in larger (societal) systems. Consideration of different systems levels important. #2 The system analysis should always be done until national level, e.g., to understand infrastructure. #5
- The time intensity of understanding the system needs to be considered: focus on collecting relevant information rather than all information. #5; #6
- Long term outlook important. #7

CM Factor 2: Comprehensive Analysis

- Important to map both the existing linear system and the envisioned future circular system. #4; #8
- Important to identify *what* exactly needs to change. #4
- For a comprehensive analysis, a lot of data is required. Will this data be available? #4
- Barriers of a system are important to consider. #4; #5
- Legislation and political institutions (e.g., the EU) important to consider. #4; #5; #6
- Tracking and measuring is an important activity. #5; #6; #8
- A lack of multi-decision analysis tools persists. #6
- Important to consider feedback loops (of processes). #1; #3
- Gap between life cycle assessments, the assessment of carbon and financial flow assessments exists. Machine Learning could support this process. #5
- Need to consider different levels of circularity. #6; #8
- Measurements for value underdeveloped. #8

CM Factor 3: Adaptation

- Innovation is important but it is necessary to understand what exactly needs to be innovated: the system, the product, the material? #4
- Innovation in non-technical areas is important. Example: do new players need to join? #4
- Extra costs for knowledge creation can occur. #5
- Dynamic capabilities are hard for large companies. #5
- Openness for knowledge sharing required for collaboration. #6; #8
- Learning and unlearning important. #7, #8

CM Factor 4: Collaboration

- Collaboration is essential. #4; #6 This factor covers the *people element*. #4
- All stakeholders should be considered and if possible involved. #4; #6
- Stakeholder involvement is essential because there is a lot of inertia to change. #4
- Many silos exist within companies. #4; #5; #8
- More collaboration within one organisation (between departments) required. #5
- Familiarity between collaborators needs to be established. #4
- Responsibilities need to be clearly defined. #4
- Trust as a key enabler. #4; #5
- Shared work needs to be balanced with work delegation – work should be delegated according to expertise. #5

CM Factor 5: Governance

- Central organising entity is required to oversee process. #6
- Transparency and accountability are very important. #1
- Training of the people involved, e.g., the board members of a company, is important. #1; #8
- Formal and informal agreements both have an important part. But, at the moment, many informal agreements exist which is not sustainable (not possible to engage in large collaborations this way) #4
- The usefulness of contracts is context dependent. #6
- Hard to install trust between competitors. #5
- Development of a culture important. #7

Learnings for the individual flows

Material

- Necessary to understand the value / the service that a material delivers in order to find alternatives. #1
- CE is a material-based concept so all other flows should in turn be second to that. #4

Energy

- Energy flows are inherent in every process that takes place. #1
- The carbon of energy flows needs to be considered for all processes. #5
- A lack of explicit consideration of energy requirements persists in the literature. #7

Value

- Necessary to understand the value that a product delivers (i.e., which services it provides, which needs it satisfies) #1
- Rebound effects also play an important role for value. #1; #8
- Value has only been started to be incorporated in the study of metabolisms since recently. #3
- Not just social, environmental, and economic value needs to be considered. Other perspectives should be included as well, e.g., value for customers, for businesses, for the product. #4
- Detailed definition of value required. #4; #5; #6 (Especially environmental and social value defined very broadly at the moment. #6)
- Value can be defined in very diverse ways #4 and is often understood differently by each organisation (#5). It is a developing concept. #7
- The redistribution of value is important and must be done in a fair and appropriate way. #5; #6 Existing contractual agreements can be a barrier for this. #5
- Large scale societal transformation is necessary, and with that a rethinking of value and the value propositions of product to successfully implement circular value networks. #1; #2; #6

Information

- Three key pieces of information often required are: the source, the target and the amount (of the flow, e.g., resources, money, etc.) #5; #6

Appendix 5 Summary of workshop findings

The summary of the workshop findings combines the notes taken by the facilitator during the workshop and the results of the interactive activity (presented in Appendix 6). Given the number and the size of the workshop groups, the facilitator could not supervise and direct the conversation (as it was the case during the expert interviews). Therefore, the decision was made not to post any previous results on the canvas to avoid confusion and uncertainty. The participants worked on a clean canvas and did not react to the previously developed factors and enablers. The results developed on the canvases by the groups were afterwards allocated to the circular metabolism factors as the facilitator saw fit. This resulted in the summary of the results as presented in the subsequent table.

Framework findings based on interactive activity

Holistic Approach

- Identification of internal and external stakeholders and their responsibility in the process. (A)
- Consider the arguments and reasons of other stakeholders. (B)

Comprehensive Analysis

- Clear objectives (and needs to be fulfilled) must be defined to start. (A; B) Start with the *why*. (B)
- The contribution of the circular metabolism to business objective should be defined. (A)
- Information on components, ingredients and supplied goods required. (A)
- Map value chain and internal actors. (A)
- Sustainability guidance should be provided. (B)
- Consider regulation. (B)
- Maturity level analysis to understand where the company or brand is currently positioned. (B)
- Performance measurement important to assess choice of strategies. (B; C)
- Consider risks. (C)
- Feedback conversation between actors (A; C)

Adaptation

- Business model adaptation or new business model might be required to implement circular strategies. (A; B)
- Important to build a knowledge base. (B)
- Trainings to understand the purpose. (C)

Collaboration

- Collaboration generally important. (B)
- Engage in dialog with suppliers. (A)
- Create relationship with network. (B; C)
- Involvement of and communication with end-user. (B)

Governance

- Agreements and contracts necessary. (A; B)
- Securing data through NDAs. (A)
- Knowledge of certificates important. (A)
- Trust is important. (B; C) Install mechanisms to create trust. (C)
- Simplicity as general characteristic: simplicity of the system, easy to use processes. (B; C)
- Transparent communication to all stakeholders. (B; C) – including end-users. (B)
- Quality control necessary. (B) Creating standards. (C)
- Establishment of shared long term goals. (A)
- Coordination of current initiatives. (B)
- Share information with all relevant stakeholders in simple and intuitive way. (B)
- Incentives can help motivates actors. (C)
- Guidance helpful throughout the process. (C)

Materials

- Descriptions of product/material requirements required from producers. (C)
- Smart sorting stations. (C)
- Chemical recycling. (C)
- Extra price on virgin materials. (C)
- Leasing or take back systems. (C)
- Use of standardised data sheet focusing on material. (C)

Information

- Collecting information directly from supplier. (A)
- Data platforms helpful for the facilitation of information. (A)
- Individual should remain in control of data. (C)
- Product information to facilitate transfer of data. (C)

Value

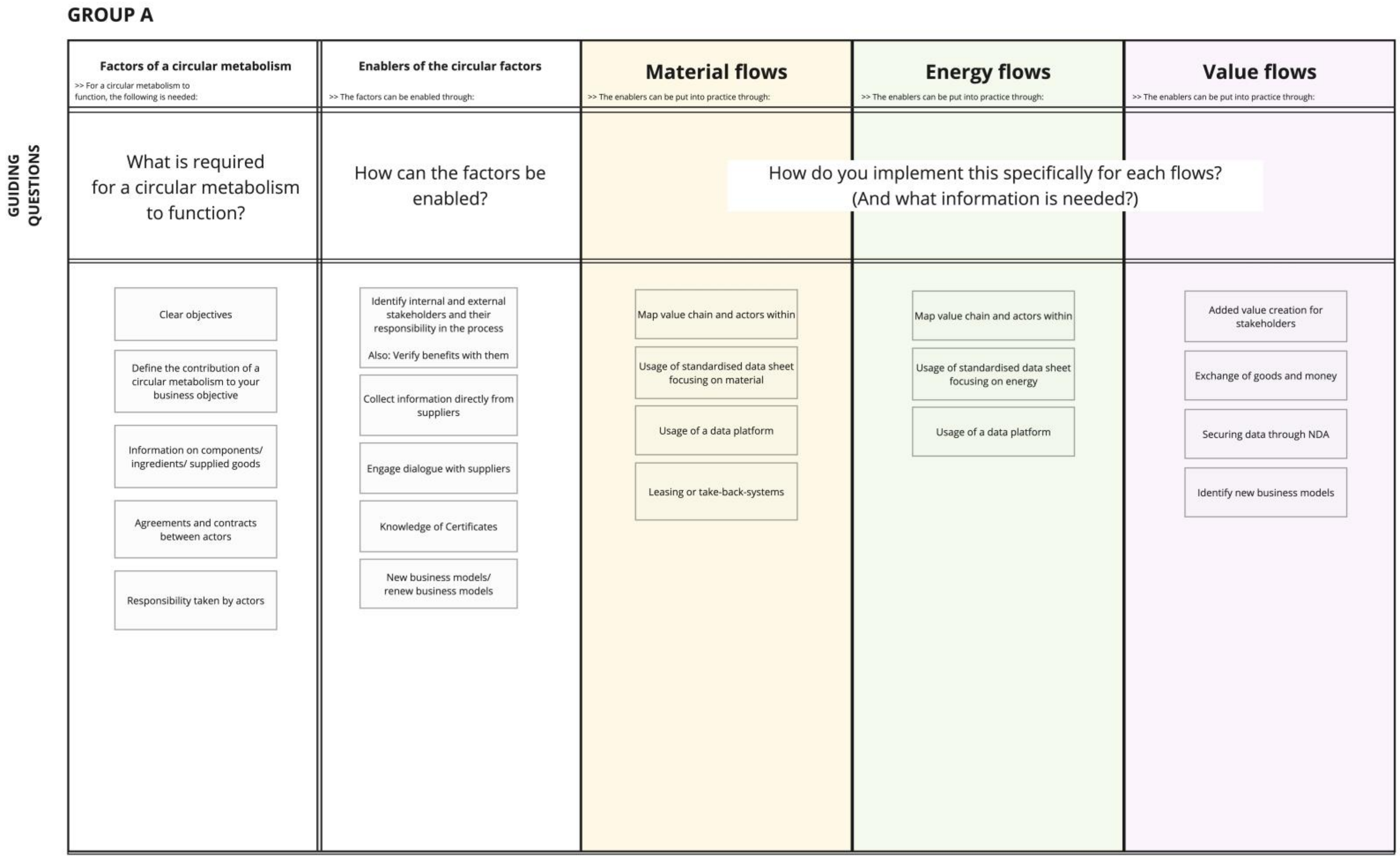
- Value requires definition. (B)
- Important to define what value is for the individual organisation. (B)
- Identify added value creation for stakeholders. (A)
- Consider emotional value of products for customers. (B)

General learnings

- Scaling processes will be important to implement circular practices. (C)
- Testing and pilot projects required. (C)
- Interoperable research page for products might be helpful. (C)

Appendix 6 Workshop canvases per group

Appendix 5 includes the canvases from the interactive activity on the online facilitation white board. The framework entries were cleaned up after the workshop for better presentation and overview. No content adjustments were made.



GROUP B

	Factors of a circular metabolism	Enablers of the circular factors	Material flows	Energy flows	Value flows
	>> For a circular metabolism to function, the following is needed:	>> The factors can be enabled through:	>> The enablers can be put into practice through:	>> The enablers can be put into practice through:	>> The enablers can be put into practice through:
GUIDING QUESTIONS	What is required for a circular metabolism to function?	How can the factors be enabled?	How do you implement this specifically for each flows? (And what information is needed?)		
	Collaboration Trust Agreements Simplicity Transparency on material (production/shipment/usage) Transparency towards end-users Create business value (1st circular product) Start with the *why* >> whats the intention behind becoming circular Clarify needs Easy to use processes Dissemination Sustainability guidances Knowledge base + link to network Regulation Data carriers vs guidelines agencies in hubs Understand where others are coming from	Waste as a resource End-user communication/involvement Quality control Interfacing across data sources / use cases / sectors Coordination of the current initiatives Provide all necessary information for all stakeholders in an intuitive, simple way Maturity levels- analysis where the brand/ construction company is actually standing			What is value? Business: Becoming a lead in creating circular products >> make money on consulting Valueable products that consumers actually have a connection too Create value by reusing a product

GROUP C

Factors of a circular metabolism >> For a circular metabolism to function, the following is needed:	Enablers of the circular factors >> The factors can be enabled through:	Material flows >> The enablers can be put into practice through:	Energy flows >> The enablers can be put into practice through:	Value flows >> The enablers can be put into practice through:
GUIDING QUESTIONS: What is required for a circular metabolism to function?	How can the factors be enabled?	How do you implement this specifically for each flows? (And what information is needed?)		
Transparency	Data share control	Trusting mechanisms / experts - capacity building		Extra price on virgin material
Communication	MDS/SDS for waste	Describe waste		
Trust System	Network for industry waste - estimate value	Trainings to understand the purpose		
Transparency towards end-users	Testing and Pilot Projects (Network of Testing/Pilot that you built trust and not afraid)	Smart sorting stations		
Transparency on material (production/shipment/usage)	Product Information System	Chemical recycling		
Start with the why	Incentives	From the waste perspective need a description from producers what they want / need as product		
Clarify needs	Make a standard	Large feedstock flows should be focus		
Scale	Guidance	Extra price on virgin material		
Cost of manage risk	Uniform everything to RDF			
Accessible (uniform)	Better description of waste - standard			
Easy (less barriers/ learning)	Gather all cost - purchase/logistics			
	Interoperable research page for products			
	Supply Security			
	No polluter pays principle			
	Capacity building - that waste is valuable			
	Everyone can access everything			

Appendix 7 The Circularity Design Framework

Circular metabolism factors	Circular Enablers	Implementation Actions		
		Material flows *The ability to:*	**Energy flows** *The ability to:*	**Value flows** *The ability to:*
The capacity to understand the system and its relations	The capacity to understand interrelations between processes and actors in the system		• understand all parts of energy (i.e., exergy and anergy) [32,57]	• consider a diverse variety of value forms (incl. economic, environmental, and social) [44,46,54,55] (#4; #5; #6; B; C)
	The capacity to identify and consider all (relevant) system actors	• identify connections by analysing (large amounts of) supply chain data [46]		
	The capacity to consider processes throughout entire life cycle	• collect data along entire supply chain [44] • observe and track materials (in real time) throughout all life cycle phases [45,46]	• collect and analyse large amount of data fast [45,63] • visualise and simulate all processes [46]	
	The capacity to understand interrelations with other systems (at different levels)	• identify connections by analysing (large amounts of) supply chain data [44]	• understand carbon intensity and sustainability of energy sources [51,82] (#5) • visualise and simulate all processes [46]	
The capacity to evaluate actions & processes	The capacity to scope (new) combinations of processes	• analyse the feasibility of resource exchange (#5, #6) • record material specifications and activities in central and standardised unit. [60] • understand the connection of the quality and quantity of flows (#1) • incorporate data from various sources [82] • visually capture processes [32,37]	• trace materials back to their origin to evaluate energy consumption [64] • identify energy requirements of rebound effects from material flows [49] • consider alternatives for achieving efficiency [63] • forecast energy demand and supply [51] • assess technical feasibility [37]	• evaluate the economic feasibility of material and energy strategies [37] • account for social and environmental externalities [47] • develop holistic value proposition [9,43,45] • identify activities for value creation, capture and delivery [58] • develop core objectives [58] • understand value created, value destroyed, value missed [58]
	The capacity to understand system barriers and external factors		• consider macro level energy infrastructure and legislature (#1)	
	The capacity to understand the effect of (a set of) actions (on the system)	• understand success factors of exchanges [55] • measure and compare material flows [57] • evaluate direct and indirect effects [83]	• evaluate energy consumption and carbon emissions [49,83] • analyse large amount of data fast [45] • manage the dynamic and complexity of energy data [63] • measure rebound effects [49] (#1) • establish (prompt) feedback structures [63]	• measure economic, environmental and social value each [66] • combine all dimensions of value for a comprehensive evaluation [57] • assess value created, missed, destroyed [58]

The capacity to adapt	The capacity to acquire and share (new) knowledge	• track actions and decisions made by system actors [46]	• collect data during all life cycle phases [51,63] • incentivize the sharing of data [40]	
	The capacity to develop new configurations	• understand the qualities and characteristics of a material (#1; A)	• collect and process dynamic and complex energy data quickly [45,63] • simulate processes to identify efficiency potential [46]	• define different types of value [38] • understand underlying needs and wants [38,83]
The capacity of actors to collaborate	The capacity to work together for a shared goal	• share infrastructure (Hardware and software) [6,37] • align processes [6] (C)	• share infrastructure (Hardware and software) [37] • collaborate for energy recovery [37] • bring together all energy sector stakeholders [51] • share information on energy demand and surplus [37,40]	• collaborate for value (co)creation, value transfer and value capture [6]
	The capacity to integrate (relevant) actors throughout entire process	• incentivize cooperation [64] • establish reciprocal information exchange [64]	• allow and encourage active engagement by users (i.e., prosumers) [51] • collect and provide consumption data during use phase [40]	• include stakeholders during identification of value [9] • integrate stakeholders in evaluation processes [54]
The capacity to manage the system	The capacity to coordinate processes and actors for the benefit of the system	• manage risk in case of exchange failure [37]	• manage energy exchanges decentralised [51,56] • make decisions automatically [56]	• establish shared vision and align objectives [50,71] • ensure that responsibilities and obligations are met [37]
	The capacity to interact and share information with actors in an effective and trustful way	• share information transparently and traceably [51] • standardise material information (C)	• share information transparently and traceably [51,56]	• verify value creation [83]