



What Makes the Difference?

How Terminological and Conceptual Distinctions
Constrain Integration between Material Flow Analysis Data,
Supply-Use Tables and Input-Output Tables



In fulfillment of the requirements for
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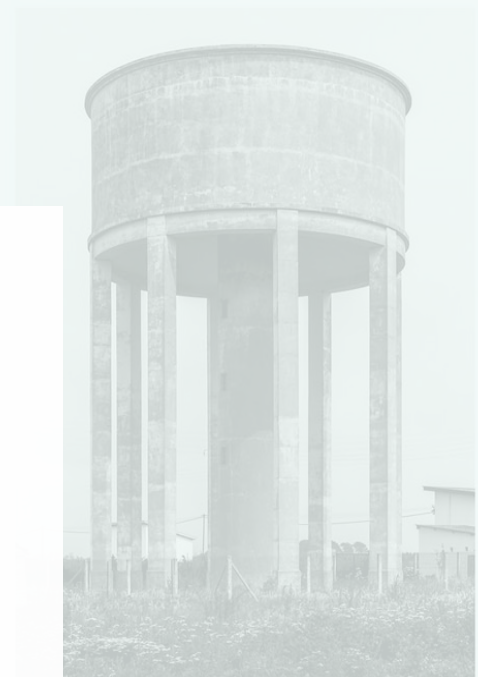


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Abstract

Despite similarities between Material Flow Analysis (MFA) and Input-Output Analysis (IOA), integration between the two has so far remained limited. This thesis conducts a critical comparison eleven to better undistinct data types used in MFA and IOA, to better understand what obstacles hold back integration. Unlike earlier studies, which focused on similarities in purpose and data structure, the emphasis of this thesis is on terminology and conceptual interpretation, which until now have not been clearly reviewed and articulated.

Key contributions of this thesis include conceptual clarification and recommendations on the use of terminology, as well as a method-neutral conceptual framework to use where conventional terminology proved insufficiently precise. Together, these strategies improve conceptual clarity and precision, reduce misunderstandings when discussing multiple data types simultaneously, and make it easier to discuss conceptual similarities between data types.

The critical comparison, conducted with help of a novel conceptual mapping approach, finds that differences between MFA data, Supply-Use Tables (SUTs), Input-Output Tables (IOTs), and their subtypes stem from four key sources: (i) a lack of terminological alignment between MFA and IOA; (ii) misalignment of system boundaries and disaggregation schemes; (iii) varying units-of-account; and (iv) the one-to-one correspondence requirement between products and industries in IOTs. Only the latter two relate to fundamental characteristics of data types. Misalignment of terminology, system boundaries and disaggregation schemes could in principle be addressed by revising or adapting established conventions.

From these findings, the conclusion is drawn that no insurmountable barriers stand in the way of integration or unification MFA data with Physical Supply-Use Tables (PSUTs). Because the System of National Accounts (SNA) and System of Environmental-Economic Accounting (SEEA) are already well-established and guarantee alignment with a broad range of other economic statistics, the most promising route to integration seems to be for MFA practitioners to seek alignment with these frameworks and/or adopt a PSUT format for storing data. This would increase the comparability and reusability of material stock and flow data, while also strengthening the case for systematic data collection.

Finally, this thesis emphasizes that differences between monetary and physical data cannot be overcome with simple unit conversions, even when using sophisticated models such as WIO-MFA. It therefore points to multilayer Hybrid Supply-Use Tables (HSUTs) as a promising approach to integrate monetary and physical data for comprehensive analyses of socio-economic metabolism.

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Declaration on the use of Artificial Intelligence

In writing this thesis I have used the AI tool ChatGPT (versions GPT-4 and GPT-5) to assist me in the following ways:

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- (iii) To suggest improvements to legibility and flow during the final editing of the thesis.

I have not used ChatGPT or any other AI tool to generate or rewrite full paragraphs. The problem definition, analysis, and conclusions presented in this thesis are entirely my own.

Table of Contents

1 Introduction	1
2 State-of-the-Art	3
2.1 Distinct Subtypes of MFA Data	3
2.1.1 'Generic' Material Flow Analysis Data	4
2.1.2 Economy-Wide Material Flow Accounting Data	4
2.1.3 Materials System Analysis Data	5
2.2 Distinct Subtypes of IOA Data	5
2.2.1 Supply-Use Tables versus Input-Output Tables	5
2.2.2 Physical IOA Data	6
2.2.3 Monetary IOA Data as Proxy for Physical Flows	7
2.2.4 Extended IOA Data	7
2.2.5 Hybrid-unit IOA data	8
2.2.6 Multilayer Hybrid IOA data	8
2.3 Conceptual Overlap Between Data Types	8
2.3.1 Definition of Shared Graph-based System Structure	8
2.3.2 Applications of Neutral Graph-based Frameworks	9
2.3.3 Future Outlook: True Unification Between Data Types?	9
2.4 Unexplored Barriers to Integration	10
3 Research Objective	11
4 Methodology	12
4.1 Preliminary Steps to Enable Comparison	12
4.1.1 Distinguishing Data Types from Broader Analytical Frameworks	12
4.1.2 Defining Conventional Interpretation of Data Types	13
4.1.3 Developing a Method-Neutral Conceptual Framework	14
4.2 Critical Comparison of Terms and Definitions	15
4.2.1 Conceptual Mapping using Method-Neutral Conceptual Framework	15
4.2.2 Initial Assessment of Terminological and Conceptual Alignment	16
4.2.3 Closer Conceptual Comparison of Similar Concepts	16
5 Results	17
5.1 Neutral Conceptual Framework	17
5.1.1 Fundamental Building Blocks to Form Basic Framework	17
5.1.2 Conceptually Distinct Node Subtypes	19
5.1.3 Conceptually Distinct Flow Subtypes	21
5.2 Conceptual Mapping	22
5.2.1 Clarification of IOA Terminology to Support Conceptual Mapping	22
5.2.2 Results of The Conceptual Mapping	24
5.3 Initial Assessment of Conceptual Alignment	27
5.3.1 Conceptual omissions	27
5.3.2 Conflicting Terminology	27
5.3.3 Comparable Concepts and Aligned Terminology	28
5.4 Closer Conceptual Comparison	30
5.4.1 Implementation of System boundary	30
5.4.2 Interpretation of intermediate nodes	32
5.4.3 Implementation of balancing equations	36
5.4.4 Interpretation of stocks and capital	38
5.4.5 Implementation of disaggregation schemes	41

6 Discussion	43
6.1 Synthesis of Key Findings.....	43
6.1.1 Obstacles to Clear and Precise Methodological Discourse	43
6.1.2 Terminological Alignment between Data Types	45
6.1.3 Points of Conceptual Clarification to Support Findings	45
6.1.4 Irreconcilable Conceptual Differences between Data Types.....	47
6.1.5 Convention-bound differences between data types	48
6.2 Answers to Research Questions.....	50
6.3 Implications	54
6.3.1 Strategies to Increase Conceptual Clarity Within MFA and IOA.....	54
6.3.2 Pathways Towards Further Integration Between MFA and IOA Data	55
6.4 Reflection on Methods	57
6.4.1 General Research Limitations.....	57
6.4.2 Reflection on Method-Neutral Conceptual Framework.....	58
6.4.3 Reflection on Conceptual Mapping Approach.....	59
7 Conclusion	61
8 Recommendations	62
8.1 Recommendations for Methodological Research.....	62
8.2 Recommendations to MFA Practitioners	63
8.3 Recommendations to IOA Practitioners	64
References	65
Appendix A - Conventional system structure per data type	69
Appendix B - Elaboration on neutral conceptual framework	75
Appendix C - Supl. Material for Conceptual Comparison	76

List of Figures

Figure 2.1: Distinct subtypes of MFA and IOA data used to record material stocks and flows within the economy.	3
Figure 4.1: Largely independent steps within the analytical frameworks of MFA and IOA.	12
Figure 4.2: Schematic visualization of conceptual mapping approach used for initial comparison.	15
Figure 5.1: Visual conceptualisation of our method-neutral conceptual framework.	18
Figure 5.2: How stocks in MFA diagrams are interpreted in a directed graph structure.	20
Figure 5.3: The overlap and differences between various definitions of the economic boundary.	31
Figure 5.4: Schematic overview showing the overlap and differences between different units-of-account.	32
Figure 5.5: Examples showing when subjective allocation is needed for a given analytical purpose.	33
Figure 5.6: Implicit markets included in IOTs due to one-to-one correspondence between products and industries.	34
Figure 5.7: Example showing how disaggregation into sub-markets can ensure traceability of distributive nodes.	35
Figure 5.8: How stock mutations are recorded differently in depending on system boundary.	38
Figure 6.1: Proposed naming conventions that more clearly reflect key distinctions between data types.	54

List of Tables

Table 4.1: Literature used to define a 'conventional' terminology and structure of data types.	13
Table 5.1: Fundamental conceptual building blocks of our method-neutral conceptual framework.	18
Table 5.2: Conceptually distinct node subtypes defined within this thesis.	19
Table 5.3: Conceptually distinct flow subtypes defined within this thesis.	21
Table 5.4: Conceptual mapping of method-specific concepts unrelated to nodes and flows.	24
Table 5.5: Conceptual mapping of method-specific concepts related to nodes.	25
Table 5.6: Conceptual mapping of method-specific concepts related to flows.	26
Table 5.7: Comparison showing how system boundary criteria are implemented differently across data types.	30
Table 5.8: Overview comparing what balancing equations are implemented in each data type.	36
Table 5.9: Comparison showing what characteristics of stocks are recorded by different data types.	38
Table 6.1: How assertions made by conceptual mapping tables highlight points of improvement at each iteration.	59

1 Introduction

The prevailing model of economic production and consumption is under pressure, due to its connection to greenhouse gas emissions, excessive material extraction and a worrying dependence on a few powerful actors for its critical materials. In response, many have emphasized the need for a transition: away from a globalized, linear and fossil-fuel driven economy, toward strategic autonomy, circularity and carbon neutrality.

Long-term sustainability policy implemented by national and international institutions is expected to play a major role in enabling this transition. Evidence-based decision-making, guided by reliable information^[1] on the macro-economic structure of the economy, is essential to ensure such policy achieves its intended goals. In particular, quantitative data on the flow and accumulation of materials throughout economic production chains is required to understand the interdependence between different actors within the economy. This thesis aims to contribute to this effort by critically comparing three commonly used families of data types and reflecting on their potential for integration: Material Flow Analysis (MFA) data, Supply and Use Tables (SUTs) and Input-Output Tables (IOTs).

>> *Practical need for quantitative material flow data*

Before focusing on these data types, it is important to emphasize the policy-relevant applications of quantitative material flow data. First and foremost, it proves useful to calculate a wide variety of descriptive indicators. For example, circularity and material efficiency indicators (e.g. Fischer-Kowalski et al., 2011; Moraga et al., 2019); criticality indicators (e.g. Graedel et al., 2015); indicators signaling problematic material flows such as environmentally harmful material extraction and environmental emissions (e.g. Wiedmann et al., 2007); or consumption-based footprint indicators to show the indirect supply-chain-wide effects of production and consumption (e.g. Tukker et al., 2016). When monitored, these indicators may for example be compared against policy targets to monitor progress and gauge policy effectiveness; compared between regions to assess relative performance; or used to contrast different products and sectors of the economy, helping to identify impact hot-spots that most urgently need addressing.

Apart from monitoring purposes, material flow data has also proven relevant to evaluate and compare hypothetical policy scenarios using prospective models. Reviews by Pauliuk & Hertwich (2016) and Wiedenhofer et al. (2024) highlight several model families that are often used for such purposes, including static and dynamic Material Flow Analysis (MFA) models (e.g. Van der Voet et al., 2002; Müller, 2004; Müller et al., 2014); Input-Output Analysis (IOA) models (e.g. Duchin, 1990; Aiguillar-Hernandez et al., 2018); Life Cycle Assessment (LCA) models; Computational General Equilibrium (CGE) models; and Integrated Assessment Models (IAMs) (e.g. Lefèvre, 2023). These models may either generate steady-state scenarios, or dynamic scenarios that incorporate how changes over time affect policy outcomes. In the former case, it is often only the flows of material within a single year that are relevant as input-data. By contrast, the latter requires reliable time-series data on both flows and accumulated stocks to model how these affect each other over time (Pauliuk & Müller, 2014).

>> *Material Flow Analysis and Input-Output Analysis*

Now back to the data types that are the focus of this thesis. Within Industrial Ecology (IE), two largely independent analytical frameworks are used to provide and analyze quantitative material flow data for both monitoring purposes and prospective modeling at a macro-economic level^[1]:

- **Material Flow Analysis (MFA):** Developed with sustainability in mind, and explicitly focuses on recording and analyzing the physical stocks and flows of materials. MFA data can cover both the economy and environment, and communicate information at various scales and resolutions: from plant- or firm-level to a macro-economic level. (Fischer-Kowalski, 1998a, 1998b, 2011; Bachini & Brunner, 2012; Brunner & Rechberger, 2017; Graedel, 2019)
- **Input-Output Analysis (IOA):** Originated as an economic method, but nowadays used extensively in sustainability analysis as well. The economic origin is reflected in a focus on transactions of economically valuable goods and services in Supply-Use Tables (SUTs) and Input-Output Tables (IOTs). These tables are typically highly standardized and provide comprehensive accounts of the structure of national economies at high sectoral resolution. (Suh, 2009; Nakamura & Kondo, 2009; United Nations, 2014, 2025; Miller & Blair, 2021; Nakamura, 2023).

[1] Life Cycle Assessment (LCA) is another methodology that is often used within the field of IE, but unlike MFA and IOA it is not typically used to inform macro-economic policymaking. This is amongst the reason why LCA is left beyond the scope of this thesis.

>> *Integration efforts between MFA data, SUTs and IOTs*

While there is considerable overlap in the purposes for which these frameworks are applied in IE, the two have largely remained separate. Even within MFA and IOA there is a wide variety of data types that are developed in parallel regardless of similar applications. A review of state-of-the-art MFA and IOA data, presented in **Chapter 2**, identifies at least 11 distinct subtypes of MFA data, SUTs and IOTs. However, the same explorative review also highlight recent studies that emphasize the similarities between these data types, and point to the potential for integration or even unification. This would eliminate much of the double work and conceptual confusion that comes with using many data types in parallel for similar purposes. Even so, this thesis argues that these studies focus too strongly on similarities in data structure, and overlook the importance of terminological and conceptual differences as obstacles to integration.

>> *Objective and structure of this thesis*

This thesis seeks to help understand how such terminological and conceptual differences affect the potential for integration between MFA data, SUTs and IOTs by providing a clear comparative overview that focuses on identifying and articulating terminological and conceptual differences.

The structure of this thesis is as follows: After an explorative literature review in **Chapter 2**, the research objective and research questions are presented in **Chapter 3**. **Chapter 4** then introduces the methodology for structuring the comparison between data types, of which results are presented in **Chapter 5**. In **Chapter 6**, key findings are synthesized, discussed and used to answer research questions one-by-one. This chapter also includes a reflection on the methods used. **Chapter 7** concludes the thesis, while **Chapter 8** provides actionable recommendations on where to focus further integration efforts, and how MFA and IOA practitioners could support such methodological development.

2 State-of-the-Art

This chapter aims to give insight into the state-of-the-art in MFA and IOA when it comes to recording stocks and flows of material within the economy. The focus here is not on analytical modeling methods, but instead on the wide variety of data types that are used to describe observed material stock and flows^[1].

Figure 2.1 provides an overview of the eleven distinct subtypes of MFA data and IOA data that were identified in the literature. These data types form the main object of analysis of this thesis, and the terms and abbreviations in these sections are used throughout this thesis. As such, **Section 2.1** and **Section 2.2** describe each data type one-by-one in somewhat elaborate detail, focusing on the distinguishing characteristics between them. Those already familiar with the different types of MFA and IOA data shown in **Figure 2.1** may skip directly to **Section 2.3**, where recent efforts to integrate different data types are discussed. From here, **Section 2.4** identifies four knowledge gaps surrounding the terminological and conceptual differences between data types that could form a barrier to further integration.

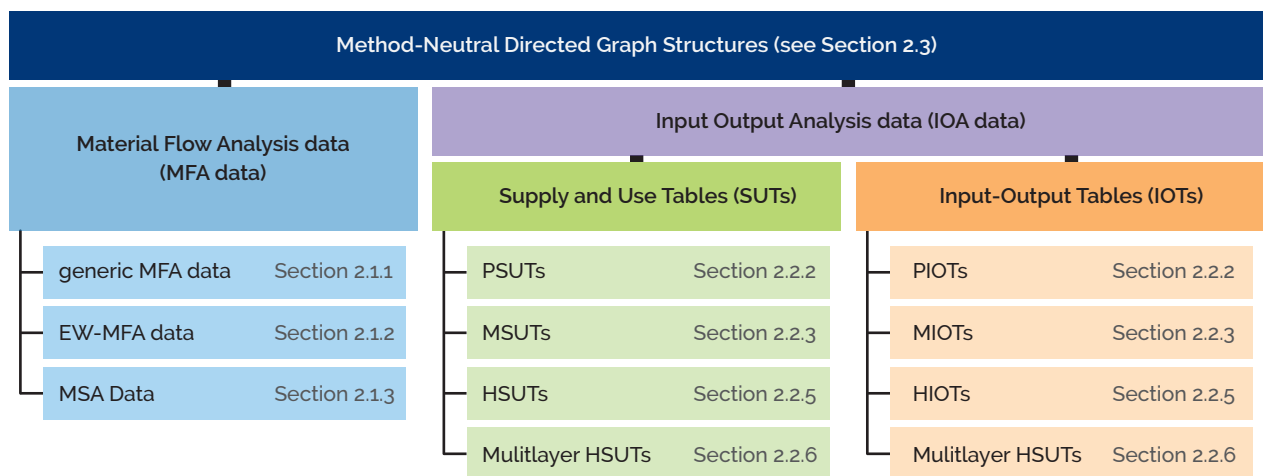


Figure 2.1: Distinct subtypes of MFA and IOA data used to record material stocks and flows within the economy.

Note. Data types are organized hierarchically, where those lower in the hierarchy are more specific implementations of those above. Section numbers indicate where data type is first introduced.

2.1 Distinct Subtypes of MFA Data

At a general level, Material Flow Analysis data (MFA data) is used to record material flows between any type of arbitrarily defined processes (Fischer-Kowalski et al. 1998; Brunner & Rechberger, 2017; Graedel, 2019). Flows are expressed in mass units and processes are typically assumed to be mass-balanced to improve robustness and guarantee internal consistency within an MFA dataset (Brunner & Rechberger, 2017; Graedel, 2019). This implies that all mass inflows to a process must either flow out or accumulate, forming a stock. These accumulating stocks are often of central interest in MFA studies, due to their implications on long-term material use and environmental pressures (Brunner & Rechberger, 2017; Graedel, 2019). MFA data is often visualized in Sankey diagrams (Brunner & Rechberger, 2017; Graedel, 2019), but may also be presented as matrix representations of a network (Van der Voet et al., 1995; Pauliuk et al., 2015; Myers et al., 2018).

From the reviewed literature, three distinct subtypes of MFA data are identified within the general family of MFA data. Each of these subtypes is discussed individually in the upcoming sections:

- (i) 'generic' Material Flow Analysis data (Section 2.1.1)
- (ii) Economy-Wide Material Flow Accounting data (Section 2.1.2)
- (iii) Material System Analysis data (Section 2.1.3)

[1] **Section 4.1** clarifies this distinction when further defining the objects of analysis for this thesis

2.1.1 'Generic' Material Flow Analysis Data (i.e. generic MFA data)

The vast majority of MFA data is created using largely nonstandardized approaches, and advice on methodological best-practices is scattered throughout the academic literature (e.g. Bachinni & Brunner, 2012; Brunner & Rechberger, 2017; Graedel, 2019). This makes it hard to provide a more strict definition than is given in the introduction of Section 2.1. Nevertheless, it is useful to distinguish this general MFA data from other more standardized subtypes of MFA data. For this reason, the term generic MFA data will be used throughout the thesis to refer to MFA data not bound by any standardized accounting framework.

Regardless of the lack of clear definition, some examples may clarify the typical application of generic MFA data. Generic MFA data is often produced by companies or academic researchers to answer a specific question, and generally focusing on the flows of a handful of specific reference materials within a limited spatial boundary and timeframe (Chen & Graedel, 2013; Graedel, 2019; Meyers et al., 2018). Its primary purpose is often to record material flows between economic activities, but environmental processes may be included as well (Graedel, 2019). Environmental nutrient cycles for example (van der Wiel et al., 2019). Unlike many other data types discussed in this thesis, generic MFA data is often used to describe specific supply chains of individual sectors or products (e.g. buildings, electric vehicles), instead of comprehensively describing the structure of the full economy at a macro-economic level (Myers et al., 2018).

On the one hand, the flexibility of generic MFA data allows MFA datasets to be made for practically any system of material flows for which data is available (Brunner & Rechberger, 2017). On the other hand, it has led to ad-hoc and intransparent methodologies, resulting in limited comparability and reusability of generic MFA data (Pauliuk et al., 2020). This has especially limited the usability of independently created sets of generic MFA data for monitoring material flow indicators over time, or for cross-regional comparisons. For these purposes, consistent time-series data is needed which is comparable across regions (Graedel et al., 2019).

2.1.2 Economy-Wide Material Flow Accounting Data (i.e. EW-MFA data)

Economy-Wide Material Flow Accounting (EW-MFA) data is a widely used tool to inform national and international policymaking about material use and circularity (Eurostat, 2018; UNEP, 2023). It gives insight into the yearly material flows that enter, exit and accumulate within a single economy at a highly aggregated level (Fischer-Kowalski, 2011; Krausmann et al. 2017; Eurostat, 2018; UNEP, 2023). EW-MFA data is produced regularly by national statistical offices, and unlike generic MFA data its structure is highly standardized. For example through the United Nations Handbook on EW-MFA (UNEP, 2023), the Eurostat Handbook on EW-MFA (Eurostat, 2018) and a dedicated chapter in the System of Environmental-Economic Accounting^[1] (SEEA) (United Nations, 2014). This standardization has enabled the compilation of consistent EW-MFA data time-series for most regions in the world, allowing for cross-regional comparisons and monitoring of headline material flow indicators over time (Krausmann et al., 2017; Wiedenhofer et al., 2019; Schandl et al., 2018, 2024; UNEP, 2023).

A major drawback of EW-MFA is that it often only considers four highly-aggregated material categories (i.e. biomass, fossil energy carriers, metals and non-metallic minerals) and treats the economy as a single black-box process, for which the internal flows are not recorded (Fischer-Kowalski, 2011; Krausmann et al. 2017; Eurostat, 2018; UNEP, 2023). If sufficient data is available, some disaggregation into more specific material classes and/or individual supply chain stages is possible within the EW-MFA framework (Eurostat, 2018; UNEP, 2023). For example, Plank et al. (2022a, 2022b) have produced disaggregated EW-MFAs for 177 countries, covering the flow of 14 major stock-building materials (e.g. concrete, steel, bricks) between 7 supply-chain stages within the economy.

[1] The System of Environmental-Economic Accounting (SEEA) also covers Physical Supply-Use Tables (PSUTs) and Physical Input-Output Tables (PIOTs), subtypes of IOA data that are discussed in **Section 2.2.2**.

2.1.3 Materials System Analysis Data

(i.e. MSA Data)

The standardization of EW-MFA provides great benefits over generic MFA data when it comes to encouraging consistency and improving the comparability of independently compiled datasets. However, the material categories of EW-MFA are too broad to provide meaningful insight into the use, circularity and criticality of specific materials. To address this, the EU has developed the Material System Analysis (MSA) framework for creating periodic, material-specific material flow datasets using a consistent methodology (BIO by Deloitte, 2015; Torres de Matos et al., 2020a, 2022). So far, the MFA methodology and corresponding data type have been used to record and analyze the flows of 37 materials used within the EU. These are mostly critical metals used for high-tech applications, but also include major materials used in the construction supply chain, such as aggregates, iron, coking coal, aluminum and copper (Bio by Deloitte, 2015; Passarini et al, 2018; Torres de Matos et al, 2020b, 2021). Nevertheless, the level of detail provided on the supply chain is still low, only distinguishing between six lifecycle stages: extraction, processing, manufacturing, use, collection and recycling (BIO by Deloitte, 2015; Torres de Matos et al., 2020a, 2022).

2.2 Distinct Subtypes of IOA Data

Broadly speaking, Input-Output Analysis (IOA) is concerned with investigating the interdependence between economic sectors by analyzing the transactions of goods and services between them (Miller & Blair, 2021). Two distinct families of IOA data are used to record these transactions: Supply-Use Tables (SUTs) and Input-Output Tables (IOTs). Because there are more similarities than differences between SUTs and IOTs, they are jointly discussed throughout this chapter, starting with a general description in **Section 2.2.1**. The sections that follow discuss subtypes of SUTs and IOTs, which are distinguished by unit(s) in which transactions are recorded:

- (i) Physical SUTs and IOTs (PSUTs and PIOTs) directly record material flows in mass units (**Section 2.2.2**)
- (ii) Monetary SUTs and IOTs (MIOTs and PIOTs) record transactions of valuable goods and services in monetary units such as euros (**Section 2.2.3**). To increase their usefulness for analyzing material flows, MSUTs and MIOTs may be extended with non-monetary satellite data. These extended SUTs and IOTs are however not considered distinct data types within the context of this thesis (**Section 2.2.4**)
- (iii) Hybrid-unit SUTs and IOTs (HSUTs and HIOTs) do not require all data to be expressed in a single unit, and may record both monetary and physical data in a single table (**Section 2.2.5**)
- (iv) Multilayer hybrid SUTs and IOTs (multilayer HSUTs and HIOTs) simultaneously record multiple aspects of the same transactions in parallel using multiple SUTs or IOTs, each expressed in a different unit (**Section 2.2.6**)

2.2.1 Supply-Use Tables versus Input-Output Tables

(i.e. SUTs versus IOTs)

As their names suggest, SUTs and IOTs record transactions between different sectors of the economy using a tabular or matrix format (United Nations, 2018). The difference between SUTs and IOTs lies in the structure of these tables.

SUTs consist of two complementary tables: the supply table and the use table. Both have a product-by-industry structure, which implies that each row corresponds to a unique product, while columns represent industries (i.e. sectors). Each entry in the supply table represents the amount of a certain product (row index) which is supplied by a given industry (column index). Similarly, entries in the use table represent the amount of a product (row index) that is used by each industry (column index). To guarantee consistency between the two tables, the total supply of each product must equal its total use. Total supply and total use are represented by the row totals of the supply and use table (United Nations, 2018). It is important to note that in the use table, all uses of a given product type are often recorded within a single row, without specifying which industry supplied them. Majeau-Bettez et al. (2016) note that this pooling of products from different suppliers limits what they call traceability: the ability to unambiguously determine the origin of a given flow.

SUTs are often used as an intermediate step in the compilation of Input-Output Tables (IOTs), which combine the information of the supply and use tables into a single industry-by-industry or product-by-product table (United Nations, 2018). For simplicity, this thesis focuses on industry-by-industry IOTs, where each entry represents a flow from one industry (row index) to another (column index). This symmetrical structure of IOTs provides various modeling benefits over SUTs (Hoekstra, 2010; Miller & Blair, 2021).

In principle, SUTs and IOTs could be used as generic data types just as MFA data, adapting their structure on an case-specific basis to fit the problem at hand. In practice however, most conventional SUTs and IOTs are compiled according to strict methodological standards. These are laid out in the Handbook of Supply and Use Tables and Input-Output Tables (Handbook of SUTs and IOTs) (United Nations, 2018), the System of National Accounts (SNA) (United Nations, 2025) and the System Of Environmental-Economic Accounting (SEEA) (United Nations, 2014).

2.2.2 Physical IOA Data

(i.e. PSUTs and PIOTs)

Physical Input-Output Tables (PIOTs) and Physical Supply-Use Tables (PSUTs) are recorded in mass units and are explicitly meant to record data on the flow of materials within the economy. The conventional methodology for compiling PSUTs and PIOTs is laid out in the Handbook SUTs and IOTs (United Nations, 2018) and the System of Environmental-Economic Accounting (SEEA) (United Nations, 2014, 2017). Compared to standardized MFA data such as MSA and EW-MFA data, PSUTs and PIOTs typically record material flows within the economy recorded at a significantly higher sectoral resolution. PSUTs in particular can be thought of as a further articulation of EW-MFA data, which is also closely aligned with the SEEA (United Nations, 2014; Eurostat, 2018; UNEP, 2023). Importantly, the SEEA has been developed to complement the (monetary) System of National Accounts (SNA) (United Nations, 2025), extending it with physical dimension to give comprehensive insights into the structure of an economy (United Nations, 2014, 2017, 2018).

PSUTs and PIOTs have a long history, as illustrated by early proposals from Konijn et al. (1997) and Hoekstra & van den Berg (2006). Nevertheless, interest in them has long remained low. This can largely be attributed to lack of reliable input data on material flows, and a reigning perception that the benefits of physical IOA data over monetary IOA data are not great enough to justify the large investments needed to compile them (Giljum & Hubacek, 2009; Hoekstra, 2010). However, a growing interest in circular economy monitoring and an increased availability of material flow data (Meyer et al., 2019; Pauliuk et al., 2019; Wieland et al., 2022) has led to a renewed interest (Hoekstra, 2010). Real-life examples of national PSUTs are the Czech tables compiled by Kovanda (2019), and the Dutch Material Flow Monitor (Delahaye et al. 2023). So far, the most comprehensive examples of physical IOA data are the global Multi-Regional PIOTs developed by Wieland et al. (2022).

Nevertheless, the compilation of comprehensive and high-resolution PSUTs and PIOTs remains a time-consuming and labour-intensive endeavor which requires the integration of multiple approaches and data sources (Kovaka, 2019; Wieland et al., 2022; Delahaye et al., 2023). Many assumptions and estimations are still required to work around data constraints (Kovaka, 2019; Wieland et al., 2022; Delahaye et al., 2023). Collaborative virtual laboratories have been proposed to incrementally resolve these data constraints through collaboration and data sharing (Wiedmann, 2017; Wieland et al. 2022). Others have suggested the use of MFA approaches (Singh et al., 2017) and process engineering models (Wachs & Singh, 2018). A simpler but potentially less accurate workaround is to use monetary data as proxy to infer physical flows (e.g. Nakamura et al., 2007; Nakamura et al., 2011; Merciai, 2019; Wieland et al., 2022). This brings us to the next class of IOA data: Monetary Supply-Use Tables (MSUTs) and Monetary Input-Output Tables (MIOTs).

2.2.3 Monetary IOA Data as Proxy for Physical Flows (i.e. MSUTs and PSUTs)

The majority of available SUTs and IOTs are expressed in monetary units (e.g. euro), reflecting the roots of IOA as an economic tradition (Hoekstra, 2010; Miller & Blair, 2021). These Monetary Supply-Use Tables (MSUTs) and Monetary Input-Output Tables (MIOTs) generally constructed by national statistical offices according to the System of National Accounts (SNA) (United Nations, 2025). These national MSUTs and MIOTs may also be combined into comprehensive (global) multiregional tables, exemplified by projects such as EXIOBASE (Wood et al., 2015; Stadler et al., 2018; Merciai & Schmidt, 2018), GLORIA (Lenzen et al., 2017), GTAP-MRIO (Aguilar et al., 2019) and others.

Due to their broad availability, MSUTs and MIOTs (extended with satellite data, see Section 2.2.4) are widely used in sustainability analysis. For example to analyze indirect footprints of consumption (e.g. Giljum et al., 2015; Wood et al. 2015), environmental impacts embodied in trade (e.g. Wiedmann et al, 2007; Tukker et al., 2016), and the economy-wide effects of circularity interventions (e.g. Aguilar-Hernandez et al., 2018). An underlying assumption for many of such models is that monetary transactions can be interpreted as proxies for physical material flows. This idea is taken further by the WIO-MFA model (Nakamura et al., 2007; Nakamura et al., 2011), which has been developed to directly convert full MIOTs to physical units, facilitating the creation of PIOTs where statistical data on physical material flows is unavailable.

Nevertheless, there are significant limitations when using monetary accounts as a proxy for physical material flows. Recording transactions in monetary units necessarily excludes unpriced but environmentally relevant material flows, such as environmental emissions and waste flows (Suh, 2004; Dietzenbacher, 2005). Also, the complex relationship between product prices and material mass has been shown to introduce biases and inconsistencies when interpreting monetary transactions in MIOTs as proxies for physical material flows (Weisz & Duchin, 2006; Mercai & Heijungs, 2014; de Koning et al, 2015; Majeau-Bettez et al., 2016).

2.2.4 Extended IOA Data (not considered a distinct data type)

To improve the analytical usefulness of MSUTs and MIOTs, they are often extended with non-monetary satellite accounts which provide information that cannot be included in the main table. Some examples are the inclusion of environmental emissions data for Environmentally-Extended IOA (EEIOA) models (e.g. Leontief, 1970, Stadler et al, 2018, Aguilar-Hernandez, 2018); data on waste generation and use for Waste-Extended IOA (WEIOA) and Waste Input-Output Analysis (WIO) (e.g. Duchin, 1990, Nakamura & Kondo, 2002; Towa et al. 2020); and data on capital/stock usage for endogenizing capital in IOA (e.g. Lenzen & Treolar, 2004; Söldersten et al., 2018a, 2018b).

These satellite accounts are usually fully independent of the MSUTs and MIOTs that they are added onto, meaning they may be left out or removed without affecting the remaining data in any way. As illustrated by the example of economically-extended MFA (Kytzia et al., 2004), the ability to combine heterogeneous datasets in such a way is not at all specific to MSUTs and MIOTs. That being the case, this thesis does not treat extended SUTs and IOTs as distinct data types. Instead they are interpreted simply as collections of independent datasets whose combination happens to be useful when used in analytical models.

2.2.5 Hybrid-unit IOA data

(i.e. single-layer HSUTs and HIOTs)

Hybrid-unit Supply-Use Tables (HSUTs) and Hybrid-unit Input-Output Tables (HIOTs) combine strengths of monetary and physical IOA data by allowing different rows of the table to be recorded in different units (Hawkins et al., 2007; Towa et al., 2020a; Miller & Blair, 2021). For example, flows of tangible goods and raw materials can be recorded in mass units (e.g. tonnes), services in monetary units (e.g. euros) and energy carriers in terms of their embodied energy (e.g. MJ). This allows HSUTs and HIOTs to simultaneously describe tangible and non-tangible flows within the economy in a way that is not possible using purely monetary or physical IOA data. This is particularly useful for models meant to analyze the indirect effects of economic production and consumption (Hawkins et al., 2007; Towa et al., 2020a; Aguilar-Hernandez et al., 2018).

2.2.6 Multilayer Hybrid IOA data

(i.e. multilayer HSUTs and HIOTs)

Another way monetary and physical IOA data may be combined is in multilayer Hybrid-unit Supply-Use Tables (multilayer HSUTs) and multilayer Hybrid-unit Input-Output Tables (multilayer HIOTs). As their name suggests, these tables consist of multiple layers, each of which is a fully-fledged SUT or IOT expressed in a single unit. This allows multiple aspects of a single flow to be captured at once (e.g. mass and monetary value), giving more comprehensive insights into the structure of the economy than any single-layer SUT or IOT can provide (Merciai & Schmidt, 2018; Merciai, 2019).

What makes multilayer HSUTs and HIOTs a distinct data type rather than simply a set of independent MSUTs and PSUTs is that the different layers are linked through conversion factors such as prices (monetary to mass units) and calorific values (mass to energy units). This introduces an extra balancing dimension which guarantees consistency across layers and improves the robustness of each individual layer of the multilayer HSUT or HIOT (Hoekstra, 2010; Merciai & Schmidt, 2018; Merciai, 2019). However, like with PSUTs and PIOTs the compilation of multilayer hybrid IOA requires great amounts of input data on physical material flows. This remains a bottleneck to their further development (Merciai & Schmidt, 2018).

2.3 Conceptual Overlap Between Data Types

2.3.1 Definition of Shared Graph-based System Structure

(e.g. SEM data and UPIOM)

Regardless of their differences, the general purpose of MFA data, SUTs and IOTs is largely identical: to describe the interdependence between economic actors by recording the flow of products and materials between them. To reflect this key similarity, Pauliuk & Hertwich (2015) coin the term Socio-Economic Metabolism (SEM) data as an overarching term for MFA data, SUTs, IOTs, as well as Life Cycle Inventory (LCI) data.

Pauliuk et al. (2015) develop this concept by comparing the system structure of the above methods and developing a general system structure. They propose that all aforementioned data types can be expressed through a common system structure without loss of information. Namely, as a directed graph describing a network of flows between nodes. Here, nodes represent any arbitrary process, while flows may represent any arbitrary flow of material, energy, services, or otherwise. Pauliuk et al. (2015) subdivide nodes in SUTs and IOTs into two distinct groups: transformative nodes (i.e. sectors/industries) and (implicit) distributive nodes (i.e. market). After doing so, they show that flows are modeled exclusively between nodes of opposing groups, but never between two nodes of the same group. This gives their interpretation of SUTs and IOTs the structure of a bipartite directed graph, a subtype of the more general directed graph format underlying MFA data and LCI data. This suggests that SUTs and IOTs should be expressible as MFA data or LCI data without loss of information, while the reverse is not guaranteed.

However, Pauliuk et al. (2015) keep their discussion of nodes and flows very abstract. They focus on the similar system structure of data types, while not elaborating on the different conventional conceptual interpretations of nodes and flows in different data types. Myers et al. (2018) largely address this by conceptually developing the general system structure of Pauliuk et al. (2015) into what they call the Unified Materials Information System (UMIS). A welcome addition of UMIS is that its terminology aligns more closely with the conventional methodology and terminology of MFA and IOA, thereby improving the accessibility of this neutral framework.

2.3.2 Applications of Neutral Graph-based Frameworks

(e.g. IEDC and YSTAFDB)

As of yet, the main practical application of the generalized system structures of Pauliuk et al. (2015) and Meyers et al. (2018) is to facilitate comparison between heterogeneous datasets by allowing them to be recast into a common structure without loss of information. This idea forms the basis of two recently developed data repositories: the Yale Stocks and Flows Database (YSTAFDB) (Myers et al., 2019) and the Industrial Ecology Data Commons (IEDC) (Pauliuk et al., 2019). These databases present independently compiled datasets side-by-side using a common system structure to increase the accessibility, reusability and comparability of stock and flow data from different sources.

That said, neither the YSTAFDB and IEDC intend to reconcile data from different sources to provide a complete and internally consistent account of all material flows within an economy (Meyers et al., 2019). After all, full comparability between datasets cannot be guaranteed. Pauliuk et al. (2015) and Meyers et al. (2018) only provide a common mathematical system structure which data can be recorded into, but they do not prescribe how this data must be obtained or how different elements within this system structure must be interpreted exactly. These aspects may vary between datasets, depending on the data type and on practical considerations such as the level of data availability, the intended purpose of the dataset, and the preferences of individual dataset compilers.

2.3.3 Future Outlook: True Unification Between Data Types?

To be able to develop truly unified Socio-Economic Metabolism databases, practices on data collection must be further harmonized to ensure comparability between datasets (Pauliuk et al, 2020). In this respect, both Pauliuk et al. (2015) and Meyers et al. (2018) fail to provide a truly convincing and practical alternative to MFA data, SUTs and IOTs. A possible explanation is that in their focus on shared elements within the system structure of these data types, both Pauliuk et al. (2015) and Myers et al. (2018) fail to address key terminological and conceptual differences, such as the examples presented below.

Examples of differences that remain insufficiently addressed by Pauliuk et al. (2015) and Myers et al. (2018):

- (i) Conventional terminology for describing MFA data seems vastly different to terminology used to describe SUTs and IOTs, making it difficult to assess the true conceptual overlap between data types
- (ii) The high sectoral resolution of SUTs and IOTs is rarely matched by MFA data, which often focuses on a handful of important processes.
- (iii) Stocks play a pronounced role in MFA data, but seem less central in SUTs and IOTs.
- (iv) SUTs, IOTs, EW-MFA data and MSA data are all traditionally governed by strict methodological standards, whereas generic MFA data is only bound by loose conventions.
- (v) Conventional monetary accounts (i.e. MSUTs and MIOTs) are unable to capture non-priced material flows, whereas physical accounts (i.e. MFA data, PSUTs and PIOTs) are cannot record massless flows such as services.

Because both Pauliuk et al. (2015) and Myers et al. (2018) limit their discussion on system structure to the shared elements between data types, they inadvertently give the impression that MFA data, SUTs and IOTs are more-or-less identical. However, the fact that these data types are still mostly treated as distinct methods seems to indicate that there remain nontrivial differences between them that act as a barrier to integration.

2.4 Unexplored Barriers to Integration

The underappreciation terminological and conceptual differences by Pauliuk et al. (2015), Myers et al. (2018) and others may be partially explained the fact that comparative studies between MFA data, SUTs and IOTs are scattered throughout the literature, and generally focuses on pointing out similarities rather than articulating differences^[1]. What seems to be particularly underexplored is to what extent distinctions between methods emerge from fundamental differences, rather than terminological and methodological conventions that could, in principle, be adapted or revised. This is especially relevant for the differences between MFA data, PSUTs and PIOTs, that seem to arise largely from varying levels of standardization and in conventions on terminology, system boundary and resolution.

>> *Research gaps addressed in this thesis*

All-in-all, this thesis argues that a better understanding of the differences between data types is a prerequisite for the development of a unified system structure for SEM data that poses a convincing and practically useful alternative to conventional MFA data, SUTs and IOTs. The overarching research gap can be formulated as follows:

It is unclear how terminological and conceptual differences between various implementations of MFA data, SUTs and IOTs affect the potential for integration between these data types

Within this broad research gap lie four specific knowledge gaps that would particularly benefit from clarification. These are addressed one-by-one through the research questions presented in Chapter 3:

- (i) The explorative literature review revealed that it is difficult to maintain clarity and precision when discussing the data types that form the topic of this. To the author's knowledge, no prior research has specifically investigated what factors cause this lack of clarity, or how terminology could be improved.
- (ii) Earlier research (Pauliuk et al., 2015; Myers et al., 2018) has shown that MFA data, SUTs and IOTs can all be interpreted as different representations of an underlying directed graph structure. Despite this, conventional method-specific terminology seems to use different terminology to describe this shared system structure. The extent of these terminological differences remains unclear.
- (iii) Closely related to the point above, it is not clear to what extent terminological similarities and differences between MFA data, SUTs and IOTs reflect underlying conceptual distinctions.
- (iv) It remains unclear to what extent conceptual differences between MFA data, SUTs and IOTs could be overcome by adapting or revising established terminological and methodological conventions.

[1] A possible explanation for this is that finding similarities has greater practical benefits. After all, identifying conceptual overlap between seemingly distinct data types may open up new methodological possibilities, whereas differences mostly serve as obstacles to comparison and integration. For researchers operating within a single specialized discipline (e.g. MFA or IOA), articulating differences between data types is thus less relevant and may easily be taken for granted without being fully understood.

3 Research Objective

In **Chapter 2**, an initial review of the state-of-the-art has identified 11 distinct subtypes of **Material Flow Analysis (MFA)** data, Supply-Use Tables (SUTs) and Input-Output Tables (IOTs) that are used to record data on material flows. Regardless of this shared purpose and similarities in system structure, efforts to integrate them into a single unified system structure have so far not produced a convincing alternative to conventional MFA data, SUTs and IOTs. As argued in **Section 2.4**, an insufficient understanding of terminological and conceptual differences between data types could be a contributing factor to this.

With this in mind, this thesis aims to clarify how such differences affect the potential for integration between MFA data, SUTs and IOTs, by providing a comparative overview that focuses on articulating the conceptual and terminological differences between these data types. In doing so, each of the research gaps identified in **Section 2.4** is addressed through the research questions presented below. These questions are answered one-by-one in **Section 6.2**.

Main Research Question:

How do terminological and conceptual differences between Material Flow Analysis (MFA) data, Supply-Use Tables (SUTs) and Input-Output Tables (IOTs) affect the potential for integration between these data types?

- Subquestion 1:** What factors undermine the clarity and precision of comparative methodological discussion on MFA data, SUTs and IOTs?
(Adressed primarily in Section 4.1, Section 5.3, and Section 6.1.1)
- Subquestion 2:** To what extent do MFA data, SUTs and IOTs use similar terminology to describe their underlying directed graph structure?
(Adressed primarily in Section 5.1, Section 5.3, and Section 6.1.2)
- Subquestion 3:** To what extent do the observed terminological similarities and differences between MFA data, SUTs and IOTs relate to underlying conceptual distinctions?
(Adressed primarily in Section 5.3, Section 5.4, Section 6.1.4 and Section 6.1.5)
- Subquestion 4:** To what extent can the revealed terminological and conceptual distinctions between MFA data, SUTs and IOTs be overcome by adapting or revising established terminological and methodological conventions?
(Adressed primarily in Section 5.4, Section 6.1.4 and Section 6.1.5)

4 Methodology

This chapter describes the research approach taken to achieve the research objective and answer the research questions defined in **Chapter 4**. The main method of analysis is a critical review of the terms and definitions that define the 11 subtypes of MFA data, SUTs and IOTs identified in **Chapter 2**. This approach is laid out in **Section 4.2**.

However, in the early stages of this review the conceptual precision and clarity of this review were seriously undermined by ambiguity surrounding the precise definitions of MFA data, SUTs and IOTs. Especially when attempting to discuss these data types in a comparative context. To combat this and enable a more clear and precise comparison, a number of preliminary measures were taken to reduce this ambiguity, as discussed in **Section 4.1**. By itself, the need for such preliminary steps is already a relevant finding, as any future attempts at comparison or integration are likely to face the same obstacles as this thesis. This is further reflected on in **Section 6.1.1**.

4.1 Preliminary Steps to Enable Comparison

In this Section: The preliminary steps are discussed that aim to enable a clear and precise comparison of MFA data and SUTs and IOTs. First, **Section 4.1.1** clarifies the scope of this thesis by emphasizing the distinction between MFA data and IOA data, and the broader methodological frameworks of MFA and IOA. Second, **Section 4.1.2** designates a single literature source for each data type to define its 'conventional' terminology and structure, ensuring the objects of analysis for this thesis are well-defined. Third, **Section 4.1.3** outlines how a method-neutral conceptual framework is developed to discuss and compare the system structures of MFA data, SUTs and IOTs with greater conceptual precision.

4.1.1 Distinguishing Data Types from Broader Analytical Frameworks

To clearly define the scope of this thesis it is important to emphasize the distinction between what this thesis calls MFA data and IOA data, and the broader methodological frameworks of MFA and IOA. This terminological distinction is introduced to isolate the data types that are used for storing information on material flows (i.e. MFA data, SUTs and IOTs) from the largely independent analysis steps related to their compilation and analytical use. To further clarify this distinction, **Figure 4.1** visualizes how MFA data, SUTs and IOTs relate to other aspects of MFA and IOA that fall outside the scope of this thesis. Below, the exclusion of these aspects is motivated.

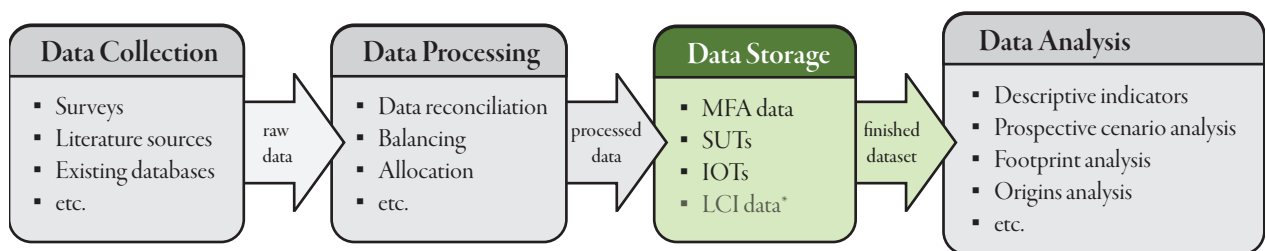


Figure 4.1: Largely independent steps within the analytical frameworks of MFA and IOA.

Note. The focus of this thesis is solely on comparing the characteristics of data types used to store information on material flows (highlighted in green).

>> Exclusion of data collection and data processing methods

The first set of MFA and IOA methods that are excluded from the comparison within this thesis are those relating to raw data collection and data processing (e.g. balancing algorithms). While these may significantly influence the usefulness and robustness of real MFA and IOA datasets, methods for data collection and data processing are only partially tied to data type. In practice, the way in which data is collected and data processing methods are applied is highly situational. It often depends on the level of data availability, the purpose of the dataset and the preferences of individual practitioners. As this variety makes it very difficult to make general observations when comparing data types, data collection and data processing methods are not considered within this thesis.

>> Exclusion of data analysis methods

The second set of MFA and IOA methods that are excluded from the comparison within this thesis are those relating to the analysis of completed MFA datasets, SUTs and IOTs. This is simply a matter of scope reduction, justified by the fact that such analytical models are independent analysis steps that do not influence the data type of their input datasets^[1]. As such, they may be disregarded in the comparison of this thesis without compromising the validity of observations made by comparing data types alone.

That said, it is important to recognize that specific data types are often closely associated with specific analytical methods used in MFA and IOA (see **Figure 4.1**). For example, MFA data is often used for origin analysis, scenario analysis or to calculate material flow indicators (Ayres & Ayres, 2002; Brunner & Rechberger, 2018; Graedel, 2019), while IOTs are often used as input data for Consumption-Based Accounting models, or econometric models (Miller & Blair, 2021).

4.1.2 Defining Conventional Interpretation of Data Types

A major obstacle in the comparison of data types is that no unequivocal definitions exist for the different subtypes of MFA data, SUTs and IOTs. Especially in the field of MFA, different authors use different vocabularies and have different preferences on how to implement these data types in practice^[2]. If unaddressed, the lack of unambiguous definition for this thesis' main objects of analysis would significantly limit the precision of the resulting comparison.

To resolve this obstacle, this thesis limits its analysis to comparing the 'conventional' interpretations of the data types identified in **Chapter 2**. To ensure consistent use of terminology, these are defined using a single primary literature source per data type, as shown in **Table 4.1**. From these sources, a conventional system structure is inferred for each data type. These are shown in **Appendix A**. Secondary literature sources are used for context only if needed to clarify definitions given in the primary literature sources.

Table 4.1: Literature used to define the 'conventional' terminology and structure of data types covered within this thesis.

Note. Secondary literature sources are only referenced when needed to clarify definitions given in the primary source.

	Data type	Primary literature source	Secondary literature sources (in order of preference)
MFA data	Generic MFA data	Brunner & Rechberger (2017)	Graedel et al. (2019); Baccini & Brunner (2012)
	EW-MFA data	UNEP (2023)	Eurostat (2023); Fischer-Kowalski et al. (2011)
	MSA data	Torres de Matos et al. (2020)	BIO by Deloitte (2015); Torres de Matos et al. (2022)
Supply & Use Tables	MSUT	United Nations (2018)	United Nations (2025); Miller & Blair (2021)
	PSUT	United Nations (2018)	United Nations (2014, 2025); Hoekstra (2010); Miller & Blair (2021)
	Single layer HSUT	Hawkins et al. (2007)	United Nations (2014, 2018, 2025); Miller & Blair (2021)
	Multilayer HSUT	Merciai & Schmidt (2012)	United Nations (2018); Hoekstra (2010)
Input-Output Tables	MIOT	United Nations (2018)	United Nations (2025); Miller & Blair (2021)
	PIOT	United Nations (2018)	United Nations (2014, 2025); Hoekstra (2010); Miller & Blair (2021)
	Single layer HIOT	Hawkins et al. (2007)	United Nations (2014, 2018, 2025); Miller & Blair (2021)
	Multilayer HIOT	Merciai (2019)	United Nations (2018); Hoekstra (2010)

United Nations (2014) = System of Environmental-Economic Accounting Central Framework (SEEA-CF)

United Nations (2018) = Handbook of Supply and Use Tables and Input-Output Tables

United Nations (2025) = System of National Accounts (SNA)

UNEP (2023) = EW-MFA handbook

[1] That is not to say that data type is unimportant for analysis purposes., as certain data types may be more useful than others as input data data depending on the modeling purpose. However, this is a topic for future research.

[2] For example: how to define system boundaries (see **Section 5.4.1**), if and how to model explicit market processes (see **Section 5.4.2**), and how to disaggregate the economy into subsectors (see **Section 5.4.6**).

>> *Definition of standardized data types*

Where applicable, documentation of standardized methodological frameworks is used as the primary literature source to define the ‘conventional’ terminology and structure of the associated data types. This is the case for PSUTs, MSUTs, PIOTs, MIOTs, EW-MFA data and MSA data. Due to the high level of standardization for these data types, there is little question that the chosen primary literature sources reflect the ‘conventional’ interpretation of these data types.

>> *Definition of non-standardized data types*

Where there is no methodological standardization, the choice of a primary literature source is somewhat artificial. In the case of HSUTs and HIOTs and their multilayer variants, research papers are used as primary literature sources. These were selected because they provide comprehensive descriptions of the data types in question, and were often cited in the literature that was explored in **Chapter 2**. For the same reasons the textbook of Brunner & Rechberger (2017) is chosen as the primary source to define generic MFA data. While other interpretations of ‘conventional’ terminology may be argued for, these sources provide widely used terms and definitions that most practitioners are likely to be familiar with.

4.1.3 Developing a Method-Neutral Conceptual Framework

A recurring obstacle encountered in writing this thesis is that MFA and IOA practitioners could interpret terms differently based on their background. As a result, using method-specific terms outside their original context may invoke conceptual confusion, complicating comparative discussion. Especially when alternating between different method-specific terminologies in the same text. Addressing this issue is a prerequisite for enabling a clear and precise comparison between data types. Not only within context of this thesis, but also in future methodological studies.

A solution to this problem is to circumvent conventional terminology altogether, and adopt an alternative, method-neutral vocabulary to use within the context of this thesis, minimizing reliance on method-specific terms carrying unwanted associations. The graph-based terminology of Pauliuk et al. (2015) and Myers et al. (2018) forms a good basis. However, because these frameworks were not designed specifically to support detailed cross-method comparison, they fail to provide sufficiently precise terminology for describing the structure of MFA data, SUTs and IOTs with the level of conceptual detail desired in the context of this thesis. So this thesis does not use the graph-based frameworks Pauliuk et al. (2015) and Myers et al. (2018) directly. Instead, these frameworks are refined and extended to create a more precise method-neutral conceptual framework to use as an analytical tool within the context of this thesis.

>> *Reinterpreting MFA data, SUTs and IOTs as directed graphs*

The primary literature listed in **Table 4.1** form the basis of our method-neutral conceptual framework. Each source defines the conceptual building blocks of its respective data type within its introductory chapters, but does so using distinct method-specific terminology: MFA data is defined in terms of processes and flows shown in Sankey diagrams, whereas SUTs and IOTs are defined in terms of rows and columns within their tabular formats. To overcome these differences, this thesis draws on Pauliuk et al. (2015), Myers et al. (2018), and a textbook on network theory (Newman, 2010) to reinterpret method-specific definitions in terms of a directed graph structure.

>> *Defining fundamental building blocks to form the basic framework*

After reviewing the aforementioned literature, a limited set of fundamental conceptual building block are defined that together characterize the structure of MFA data, SUTs and IOTs. These elements form the basis of our method-neutral conceptual framework. While a precise definition of ‘fundamental conceptual building blocks’ can be debated, this thesis uses the term to describe the most general set of conceptual elements that fulfills the conditions of mutual exclusiveness and collective exhaustiveness. In other words, all concepts of our method-neutral framework must be clearly distinct, and the full set of concepts must be able to fully describe the ‘conventional’ system structure of each analyzed data type.

>> *Conceptual refinement of basic framework*

Where deemed relevant, the fundamental building blocks of our basic framework are then subdivided into a number distinct subelements based on common conceptual distinctions within MFA and IOA. Like before, mutual exclusiveness and collective exhaustiveness is desired. The aim here is to incorporate all major conceptual distinctions that are necessary to enable a precise comparison of the system structure of MFA data, SUTs and IOTs within the context of this thesis. This refinement is based on the MFA and IOA literature presented in **Table 4.1**, as well as the earlier method-neutral frameworks proposed by Pauliuk et al. (2015) and Myers et al. (2018).

4.2 Critical Comparison of Terms and Definitions

In this section: The core research approach for this thesis is outlined. **Section 4.2.1** describes how a conceptual mapping approach is used to group comparable elements of MFA data, SUTs and IOTs. Then, **Section 4.2.2** outlines how this conceptual mapping is used for an initial assessment of the terminological and conceptual alignment between data types. Lastly, **Section 4.2.3** describes how a closer conceptual comparison of seemingly aligned concepts then aims to further articulate the similarities and differences between data types.

4.2.1 Conceptual Mapping using Method-Neutral Conceptual Framework

The primary literature listed in **Table 4.1** defines the ‘conventional’ system structure of MFA data and IOA data through a wide range of terms and definitions^[1]. To enable a structured comparison, a preliminary selection is made of method-specific terms that refer to similar underlying concepts. This is done using a self-developed conceptual mapping approach (See **Figure 4.2**): each method-specific concept defined in the primary literature presented in **Table 4.1** is mapped onto a corresponding concept of the method-neutral conceptual framework described in **Section 4.1.3**. This mapping provides a structured overview of the conceptual relationships between different method-specific terms, by clarifying which terms have comparable definitions. This overview forms the basis for further comparison.

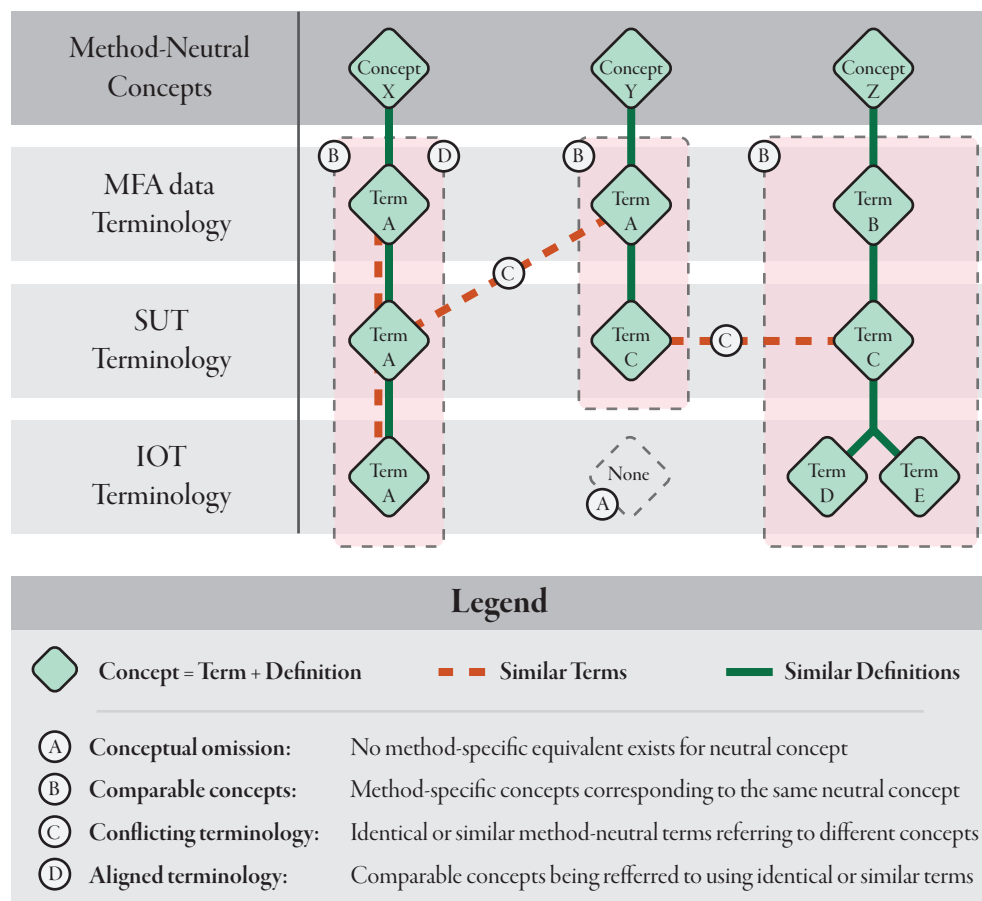


Figure 4.2: Schematic visualization of conceptual mapping approach used for initial comparison.

Note. Used for the initial assessment of terminological and conceptual alignment described in **Section 4.2.2**. In this example, the mapping of concept X shows the ideal situation where a single term is used across all data types to describe the same concept. By contrast, concept Y and concept Z show terminological misalignment: different terms are used regardless of similar definitions. There is no guarantee that comparable concepts can always be found. In this example, MFA and SUT terminology have method-specific terms corresponding to concept Y, but in IOT terminology no terms exist with a similar definition.

[1] The most important terms to describe the system structure of each data type can be found in **Appendix A**, which visually presents ‘conventional’ MFA diagrams or full SUTs and IOTs for each data type defined in **Table 4.1**.

4.2.2 Initial Assessment of Terminological and Conceptual Alignment

Using the conceptual mapping as baseline, a structured assessment of terminological and conceptual alignment is carried out by identifying which method-specific terms are mapped to each method-neutral concept (see **Figure 4.2**). This assessment serves three main purposes: (i) to pinpoint concepts that are described by data types but not in others; (ii) to highlight shared terms that can cause conceptual confusion because they describe different concepts in different data types; (iii) to identify which method-specific terms refer to similar concepts.

It should be noted that the level of detail of this initial comparison is constrained by the granularity of our method-neutral conceptual framework. As a result, the approach presented in **Figure 4.2** cannot prove full conceptual equivalence between terms. Even where terms appear synonymous there may be subtle differences in interpretation across different data types that aren't captured by the conceptual distinctions of our conceptual framework. For this reason, a closer conceptual comparison is needed to confirm if such terms are truly equivalent in meaning and use.

4.2.3 Closer Conceptual Comparison of Similar Concepts

After the initial assessment of terminological and conceptual alignment described in **Section 4.2.2** identifies seemingly comparable concepts, a closer conceptual comparison is carried out to determine to what extent the interpretation of these concepts is truly identical across data types. This comparison draws on the primary and secondary literature presented in **Table 4.1**, as well as the conceptual frameworks developed by Pauliuk et al. (2015) and Myers et al. (2018).

The main objective is to identify and clarify key conceptual differences between data types that are not yet fully articulated in MFA and IOA literature. Where necessary to clearly describe these differences, additional conceptual clarification is offered on the concepts being compared by offering a method-neutral perspective. For each identified conceptual difference between data types, a distinction is made between irreconcilable differences that are inherent to the data types being compared, and convention-bound differences that could in principle be reconciled deviating from established methodological conventions.

5 Results

This chapter presents the outcomes of the research approach described in **Chapter 4**, starting in **Section 5.1** with the method-neutral conceptual framework that is developed to improve the conceptual precision of later discussion. **Section 5.2** then applies this framework in our self-developed conceptual mapping. These sections constitute intermediate results that are mostly relevant in the way they support later comparison.

The reader that is solely interested in the similarities and differences between MFA data, SUTs and IOTs may skip immediately to **Section 5.3**. Here, the results of the conceptual mapping are used for an initial assessment of terminological and conceptual alignment. **Section 5.4** then zooms in to key concepts for a closer conceptual comparison. Many of the observations made throughout this chapter are closely interlinked. So, to provide a clear overview of all relevant results, **Section 6.1** synthesizes them into a compact number of key findings.

5.1 Neutral Conceptual Framework

In this Section: The graph-based framework of Myers et al. (2018) is sharpened to avoid the conceptual confusion that may arise when using method-specific terms outside their original context (see **Section 4.1**). **Section 5.1.1** identifies the fundamental conceptual building blocks that are needed to sufficiently describe the structure of any type of MFA data, SUT and IOT. In **Section 5.1.2** and **Section 5.1.3**, two of these fundamental building blocks, nodes and flows, are broken down further into conceptually distinct subtypes. As described in **Section 4.2**, the resulting method-neutral elements are used as the basis of the conceptual mapping of **Section 5.2**.

5.1.1 Fundamental Building Blocks to Form Basic Framework

As discussed in **Section 4.1.3**, the basis of our method-neutral conceptual framework is a set of fundamental conceptual building blocks. Nine of such building blocks were found to be sufficient to fully to define the structure of MFA data, SUTs and IOTs. These are presented in **Table 5.1**, together with basic definitions. The exact conceptual interpretation of different elements is further refined and developed throughout this thesis, especially in the remainder of **Section 5.1** and in the closer conceptual comparison of **Section 5.4**.

To supplement these terminological definitions, **Figure 5.1** provides a visual conceptualization of our method-neutral framework. Apart from providing a visual language that is used throughout this thesis, this figure also shows how our method-neutral framework relates to the conventional ways of presenting MFA data, SUTs and IOTs.

>> *Key differences compared to earlier graph-based frameworks*

The earlier graph-based frameworks of Pauliuk et al. (2015) and Myers et al. (2018) provided a solid basis for our method-neutral framework. However, three key refinements are made to increase comprehensiveness and conceptual precision:

- (i) Disaggregation schemes and balancing equations are identified as essential elements within the system structure of MFA data, SUTs and IOTs.
- (ii) Terms and definitions have been adapted to improve overall clarity and to better reflect the underlying node-and-flow structure.
- (iii) The concepts of nodes and flows are broken down into three structurally distinct^[1] elements each. This separates elements that are clearly modeled differently within the graph structure, even before considering the real-world phenomena these elements represent.

For the full side-by-side comparison of our method-neutral conceptual framework with earlier graph-based frameworks of Pauliuk et al. (2015) and Myers et al. (2018), please refer to the conceptual mapping of **Section 5.2**.

[1] In this thesis, structurally distinct elements are defined by the way in which they relate to other nodes and flows in the graph topology. In contrast, the conceptual distinctions introduced in **Section 5.1.2** and **5.1.3** define elements that may be identical from a graph topology perspective, but nevertheless represent distinct real-world phenomena.

Table 5.1: Fundamental conceptual building blocks of our method-neutral conceptual framework.

Note. Together, these mutually exclusive and collectively exhaustive elements form the basis of our method-neutral framework, which is sufficient to fully define the structure of MFA data, SUTs and IOTs. For more conceptual precision, nodes and flows may be broken down into conceptually distinct subtypes as shown in **Table 5.2** and **Table 5.3**

Distinct element	Method-neutral definition
System boundary	The criteria that define what is and is not part of the system of interest for which data is recorded
Disaggregation scheme	A systematic way by which the system of interest is split into distinct subcomponents (i.e. nodes and flows)
Balancing equations	Mathematical rules and criteria which validate the internal consistency and logical coherence of the recorded data
Nodes:	Distinct subcomponent of a networked system that receives, transforms, stores and/or redistributes flows
→ Intermediate node	→ Node with both inflows and outflows
→ Source node	→ Node with only outflows (to intermediate nodes)
→ Sink node	→ Node with only inflows (from intermediate nodes)
Flows:	Directional exchanges (of material, energy, money, etc.) from one node of a networked system to another
→ Intermediate flow	→ Flow between two intermediate nodes
→ System inflow	→ Flow from a source node to an intermediate node
→ System outflow	→ Flow from an intermediate node to a sink node

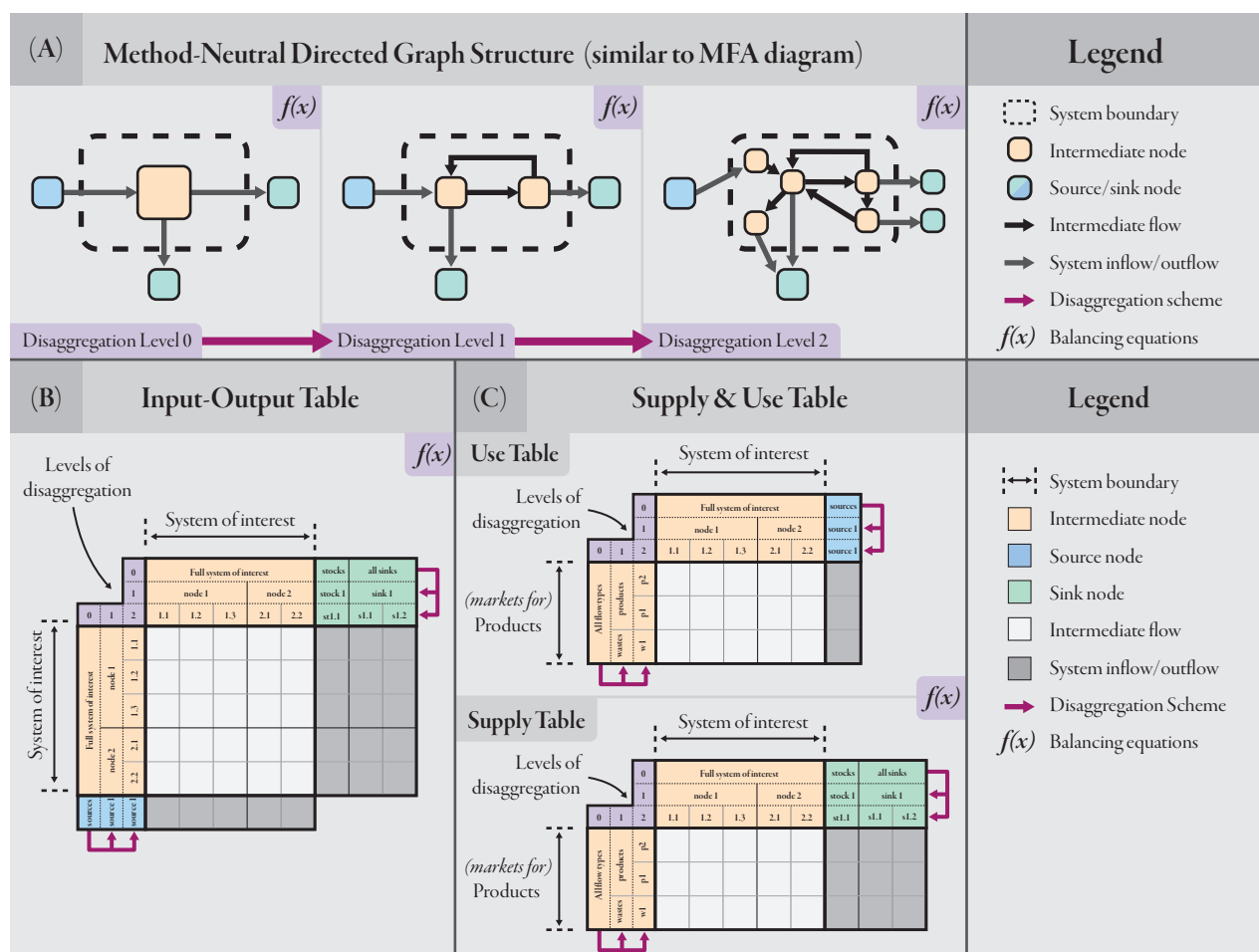


Figure 5.1: Visual conceptualisation of our method-neutral conceptual framework.

Note. This figure provides the visual language that is used throughout this thesis, showing three expressions of our framework: (A) a graph/network diagram, analogous to the process-flow diagrams used in MFA; (B) an IOT structure; (C) a SUT structure.

5.1.2 Conceptually Distinct Node Subtypes

To further refine our neutral conceptual framework, some fundamental building blocks defined in **Section 5.1.1** are broken down into conceptually distinct subtypes where deemed relevant, starting with nodes. This is done by critically reviewing the method-specific literature presented in **Table 4.1**, and the earlier graph-based conceptual frameworks by Pauliuk et al. (2015) and Myers et al. (2018). **Table 5.2** presents an overview of the resulting node subtypes. The conceptual distinctions underlying these subtypes are elaborated below.

Table 5.2: Conceptually distinct node subtypes defined within this thesis.

Note. Bold-faced rows indicate structurally distinct node types. Conceptually distinct subtypes are indicated below. Together with the elements defined in **Table 5.1** and **Table 5.3**, these form our full neutral conceptual framework.

Distinct element	Method-neutral definition	Why distinguish?
Intermediate node	Node with both inflows and outflows	Structurally distinct element
→ Transformative node	Intermediate node for which inflows and outflows are dissimilar (i.e. inflows are transformed)	To record inputs and outputs of economic activities
→ Distributive node (or market node)	Intermediate for which inflows and outflows are of the same type (i.e. inflows are not transformed)	To record trade within the system of interest
→ Storage node	Intermediate node which is connected to a stock node (not mutually exclusive with transformative or distributive node)	To record stocks with both inflows and outflows (see Figure 5.2)
Source node	Node with only outflows	Structurally distinct element
→ Stock node	Node representing a diminishing stock = origin of (net) stock outflow (defined in Section 5.1.3)	To record the use or retirement of accumulated stocks
→ Import node	Economy outside the spatial boundary from which imports are received = origin of import flow (defined in Section 5.1.3)	To record trade with entities outside the system of interest
→ Reserves node	Environmental reserves from which natural resources are extracted = origin of extraction flow (defined in Section 5.1.3)	To record resource requirements and environmental impacts
→ Other source node	Source node which cannot be classified otherwise = origin of other system inflow (defined in Section 5.1.3)	Needed for exhaustiveness
Sink node	Node with only inflows	Structurally distinct element
→ Stock node	Node representing a growing stock = destination of (net) stock inflow (defined in Section 5.1.3)	To record accumulation in stocks
→ Export node	Economy outside the specified spatial boundary to which exports are sent = destination of export flow (defined in Section 5.1.3)	To record trade with entities outside the system of interest
→ Dissipation node	Sink node representing the dissipation of material into the environment = destination of dissipative flow (defined in Section 5.1.3)	To record environmental impacts
→ Other sink node	Sink node which cannot be classified otherwise = destination of other system outflow (defined in Section 5.1.3)	Needed for exhaustiveness

>> *Modeling the economy: Transformative nodes and distributive nodes*

There is a clear conceptual distinction between intermediate nodes that represent transformative processes (e.g. industrial activities) and those that represent the simple redistribution of flows to different destinations (e.g. transport and markets). In MFA data, this distinction is often very explicit (see e.g. Graedel, 2019; Torres de Matos et al., 2020).

>> *Modeling stocks: Storage nodes and stock nodes*

An important concept in Industrial Ecology, and especially in MFA, is that of stocks. These represent accumulated stockpiles of materials (or otherwise) that may be withdrawn from at a later point in time. Examples of stocks include inventories held for later sale, infrastructure stocks, machinery and other durable goods that remain in-use for an extended period of time.

The role these stocks have in the model structure of MFA data, SUTs and IOTs is complex, and cannot immediately be described as a source, sink or intermediate node. In MFA data, a stock is modeled using three sub-elements, as shown in **Figure 5.2**: (i) A process containing a stock, which may have both inflows and outflows; (ii) The magnitude of the stock, which may either show a net increase or net decrease; (iii) An implicit flow between the process and its contained stock, representing a net addition or withdrawal to stock.

Using the node-and-flow terminology of this thesis, the first may be interpreted as an intermediate node, the second as a source/sink node^[1], and the third as a flow connecting the two. This means every stock is essentially represented using two nodes in the directed graph structure. A clear visualisation of this model structure is found in Van der Voet et al. (1995). To explicitly distinguish between the intermediate node and source/sink node that make up stocks in the system structure of MFA data, Myers et al. (2018) respectively propose the terms storage node and stock node^[2].

Admittedly, the conceptual interpretation of storage nodes remains vague, as it is difficult to give a satisfying example of a real-world phenomenon it may represent. There are few real-life economic activities whose sole purpose is to build and withdraw from stocks. Most stock-containing processes also represent transformative processes or markets (e.g. an industrial activity that maintains a stock of in-use machinery). However, for the purposes of this thesis it suffices to understand that in the abstract modeling sense, stocks in a directed graph structure are represented by two nodes that each fulfill a distinct function within the structure of MFA data, SUTs and IOTs.

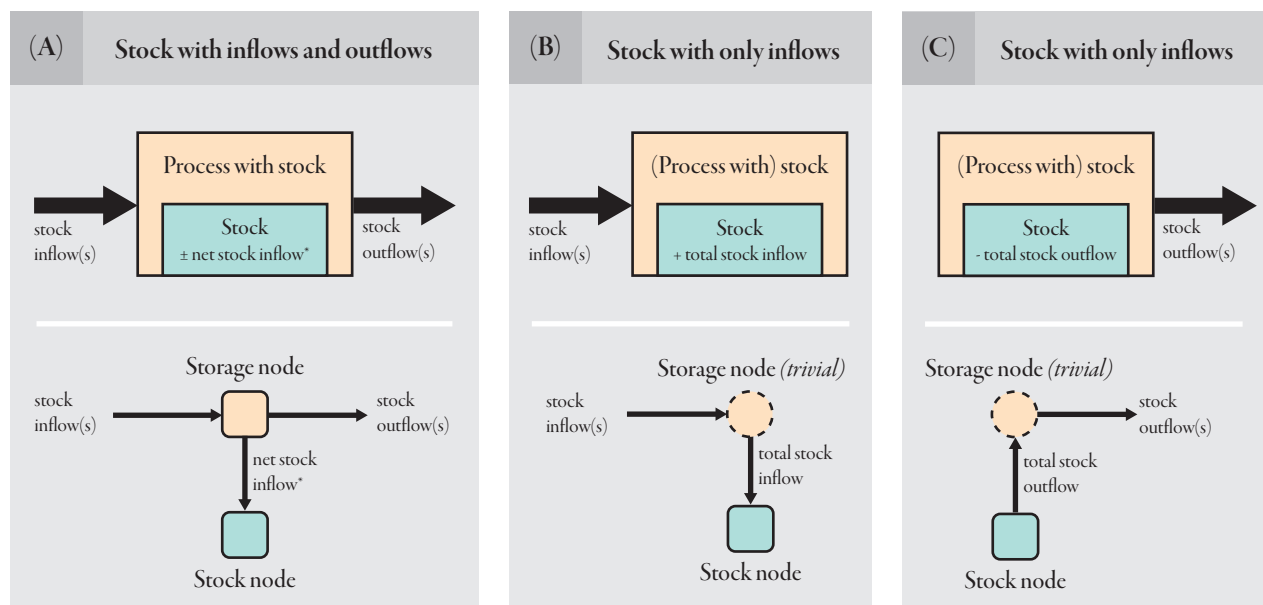


Figure 5.2: How stocks in MFA diagrams are interpreted in a directed graph structure.

Note. Depending on the situation, there are three distinct ways of modeling stocks in a directed graph structure:

(A) stock with both inflows and outflows: a distinct intermediate node and source/sink node are required in a directed graph structure to accommodate all flows. Inflow to stock node represents a net stock inflow; (B) Stock with only inflows: intermediate storage node simply aggregates inflows may be omitted without loss of information; (C) Stock with outflows: similar to stock with only inflows, but direction of flows is reversed. Intermediate storage node may be omitted without loss of information.

>> Modeling exchanges beyond the system boundary: Other node subtypes

The system of interest for MFA data, SUTs and IOTs often exchanges flows with the wider world outside the defined system boundary: be it through imports and exports, resource extraction, environmental emissions or otherwise. Modeling these flows in a directed graph structure requires both an origin and destination node to be defined (Newman, 2010), even if one of these is located outside of the system boundary. These exogenous nodes represent a distinct subtype of source and sink nodes, whose inflows and outflows are only modeled to the extent that their origin or destination lies within the system of interest. The conceptual interpretation of such nodes depends largely on the type of its associated system inflow or system outflow. This is further elaborated on in **Section 5.1.3** on conceptually distinct flow subtypes.

[1] A net increasing stock is modeled as a sink, a net decreasing stock as a source.

[2] These terms have been adapted for consistency. The exact terms used by Myers et al. (2018) are 'storage process' and 'stock'.

5.1.3 Conceptually Distinct Flow Subtypes

Like was done for nodes in **Section 5.1.2**, the concept of flows is further broken down into conceptually distinct subtypes based on a critical review of Pauliuk et al. (2015), Myers et al. (2018), and the literature presented in **Table 4.1**. The results are shown in **Table 5.3**.

Table 5.3: Conceptually distinct flow subtypes defined within this thesis.

Note. Bold-faced rows indicate structurally distinct flow types. Conceptually distinct subtypes are indicated below. Together with the elements defined in **Table 5.1** and **Table 5.2**, these form our full neutral conceptual framework.

Distinct element	Method-neutral definition	Why distinguish?
Intermediate flow	Flow between two intermediate nodes	Structurally distinct element
→ No subtypes	-	-
Source node	Node with only outflows	Structurally distinct element
→ (Net) stock outflow	(net) re-entry of previously accumulated durable assets into the economy = outflow from stock node (defined in Section 5.1.2)	To record the use or retirement of accumulated stocks
→ Import flow	Flow originating from outside the specified spatial boundary = outflow from import node	To record trade with entities outside the system of interest
→ Extraction	Extraction of material from environmental reserves = outflow from reserve node	To record resource requirements and environmental impacts
→ Other system inflow	System inflow which is not an import flow or stock outflow = outflow from other sink node	Needed for exhaustiveness
Sink node	Node with only inflows	Structurally distinct element
→ (Net) stock inflow	(net) accumulation of durable assets into a societal stock = inflow to stock node	To record accumulation in stocks
→ Export flow	Exports to other economies outside the specified spatial boundary = inflow to export node	To record trade with entities outside the system of interest
→ Emissions	Dissipation of material into the environment = inflow to dissipation node	To record environmental impacts
→ Other system outflows	System inflow which is not an export flow or stock inflow = inflow to other sink node	Needed for exhaustiveness

>> *Stock changes: Net stock inflows and outflows*

As described in **Section 5.1.2**, stocks in MFA data, SUTs and IOTs are always modeled using an (implicit) flow to represent changes in stock magnitude. If net stock change is positive (i.e. it accumulates), this flow represents a net stock inflow to the stock node, which is a sink node. If net stock change is negative (i.e. it depletes), the stock node fulfills the role of a sink node. In this case, the flow will be referred to as a net stock outflow. If stock magnitude remains unchanged, there is no flow between the stock node and its corresponding storage node.

>> *Trade flows: Imports and exports*

The system boundary of MFA data, SUTs and IOTs is partially defined in terms of specific reference region, often corresponding to an administrative or geographic region (discussed further in **Section 5.4.1**). Identifying and recording trade flows across this spatial boundary is essential to monitor the role of (international) trade in material flow networks. Trade flows come in two varieties: (i) import flows that enter the system of interest from another region. They can be seen as system inflows that originate from import nodes; (ii) export flows that leave the system of interest to another region. These are system outflows that are sent to export nodes.

>> *Environmental flows: Extraction and emissions*

The system boundary of conventional SUTs, IOTs and most MFA data excludes the environment, instead focusing on flows to, from and within the economy (see **Section 5.4.1**). However, exchanges with the environment are especially relevant to sustainability analyses due to their often problematic nature. This is why environmental flows are explicitly distinguished from other system inflows and system outflows.

The extraction of natural resources from natural reserves is represented by extraction flows, a system inflow originating from what will be referred to as reserve nodes. Likewise, emissions to soil, water or air, as well as other non-recoverable losses to the environment will be referred to as dissipative flows.

>> *Other system outflows and system outflows*

Stock changes, trade flows and environmental flows are not the only thinkable types of system inflows and system outflows. Other examples identified in **Section 5.2** are value added (system inflow) and final consumption (system outflow) in MSUTs and MIOTs, as well as all their subcomponents. However, because these are not especially relevant to the monitoring of environmental material flows they are grouped simply in the category of other system inflows and outflows without defining these further.

5.2 Conceptual Mapping

In this section: The relationship is clarified between our method-neutral conceptual framework, and the ‘conventional’ method-specific terminology to describe the structure of MFA data, SUTs and IOTs. This is done according to the conceptual mapping approach outlined in **Section 4.2.1**. However, **Section 5.2.1** first clarifies some key concepts in IOA whose relation to our method-neutral framework is not immediately clear. The results of the conceptual mapping are presented in **Section 5.2.2**.

As discussed in Chapter 4, this conceptual mapping is meant solely for use within this thesis as an analytical tool to identify how different method-specific terms relate to each other. Because the concepts most relevant for comparison are discussed in detail within these later sections, textual elaboration in this chapter is kept to a minimum.

5.2.1 Clarification of IOA Terminology to Support Conceptual Mapping

The process-and-flow structure of conventional MFA diagrams largely aligns with the directed graph structure of our neutral conceptual framework (See **Figure 5.1**). As a result, mapping method-specific concepts found in EW-MFA data, MSA data and generic MFA data to the appropriate method-neutral concepts is relatively intuitive and requires no further elaboration. However, the mapping of concepts used in IOA data may require some clarification, as their relation to our neutral conceptual framework may not be immediately clear.

This section provides a general description of these concepts to clarify why the mappings presented later are the way they are. That said, for exact definitions one should refer back to the relevant literature which is listed in **Table 4.1**. Because elaboration on method-specific concepts related to system boundary, disaggregation schemes and balancing equations would not provide any additional information beyond what is presented in the closer conceptual comparison of **Section 5.4**, this section focuses exclusively on the interpretation of nodes and flows in SUTs and IOTs.

>> *Products, residuals and natural inputs in IOA data --> Distributive nodes*

Conventional unextended MSUTs and MIOTs exclusively record the flow of economically valuable goods and services. These are collectively referred to as products. By contrast, physical IOA data must necessarily record all material flows within the system of interest to guarantee mass balance. This includes non-priced wastes and environmental flows (Dietzenbacher, 2005). In conventional PSUTs and PIOTs these residuals^[1] and natural inputs^[2] are explicitly differentiated from products and recorded in separate rows (United Nations, 2018). This structure is shown visually in **Appendix A**.

[1] The glossary definition of residuals reads: “Residuals are flows of solid, liquid and gaseous materials, and energy, that are discarded, discharged or emitted by establishments and households through processes of production, consumption or accumulation.” (United Nations, 2014)

[2] The glossary definition of natural inputs reads: “Natural inputs are all physical inputs that are moved from their location in the environment as a part of economic production processes or are directly used in production.” (United Nations, 2014)

In SUTs, rows corresponding to products, residuals and/or natural inputs occur in both the supply table and use table (see **Appendix A**), implying that these are intermediate nodes that have both inflows and outflows. The same goes for the rows that correspond to residuals in PIOTs, which appear twice: once to record the generation of residuals and once to record their use. Because none of these aforementioned row indices represent transformative activities (i.e. inflows and outflows are of the same type), all are classified as distributive nodes in **Table 5.4**. This corresponds with findings of Pauliuk et al. (2015) and Myers et al. (2018), who have both noted the implicit inclusion of markets in SUTs and IOTs.

To clarify this classification conceptually: product rows in SUTs can be interpreted as markets in the sense that they represent real transactions between economic actors. The same goes for residual rows in PSUTs and PIOTs, which mostly represent the physical trade and distribution of wastes within the economy. However, natural input rows in PSUTs can hardly be interpreted as true economic markets. Per definition, natural inputs are those flows which are extracted directly from the environment during economic production processes. As such, the interpretation of natural input rows in PSUTs should only be interpreted as distributive nodes in the abstract modeling sense. Within the structure of the PSUT they represent nodes with identical inflows and outflows, but they do not refer to trade on any real-life economic market.

>> *Gross Capital Formation in IOA data --> Stock node/stock inflow*

In both monetary and physically accounted IOA data, Gross Capital Formation (GCF) refers to the net accumulation of produced assets^[1] (United Nations, 2014, 2025). While not done so in **Table 5.4** and **Table 5.5**, GCF may be further broken down into: (i) Gross Fixed Capital Formation (GFCF), or the net accumulation of fixed assets used in economic production^[2], such as machinery; (ii) Changes in inventories, which represent stocks of goods and services retained for later use or sale^[3]; (iii) Changes in valuables, which indicate stock changes of valuable goods which are not primarily intended for use in economic production^[4]. Notably, the accumulation of consumer durables (e.g. cars) is not recorded under GCF, as they are not used in economic production. Instead, these are recorded under household final consumption.

>> *Consumption of Fixed Capital in monetary IOA data --> Stock node/stock outflow*

The aforementioned concept of fixed capital also appears in the Consumption of Fixed Capital (CFC), which represents the value depreciation of fixed assets during use^[5]. Being a value-related metric, CFC only occurs in monetary SUTs and IOTs, where it is generally recorded as a subcomponent of value added (United Nations, 2014, 2018, 2025). In the conceptual mapping, CPC is interpreted as a monetary stock outflow leaving a stock of monetary asset value (this idea is further explored in **Section 5.4.4**). However, it should be noted that the depreciation it represents does not necessarily reflect a physical stock outflow, it may indirectly result from the physical deterioration or scrapping of assets.

>> *Value added in monetary IOA data --> Other source node/other system inflow*

Very generally speaking, the concept of value added in MSUTs and MIOTs represents all value flows to productive sectors that cannot be categorized as intermediate consumption^[6], including labour income, gross operating surplus and the consumption of fixed capital. While value added primarily reflects value flows, some of its subcomponents (e.g. natural resource rents and land rents) are arguably related to underlying physical flows (United Nations, 2025).

However, whether these may be interpreted as a direct proxy for physical flows remains a complex question that is left for future research. In **Table 5.4** and **Table 5.5**, value added is simply placed in the 'other' category.

[1] The glossary definition of produced assets reads: "Produced assets are assets that have come into existence as outputs of production processes that fall within the production boundary of the SNA" (United Nations, 2014, 2025)

[2] The glossary definition of fixed assets reads: "Fixed assets are produced assets that are used repeatedly or continuously in production processes for more than one year" (United Nations, 2014, 2025)

[3] The glossary definition of changes in inventories reads: "Inventories are produced assets that consist of goods and services, which came into existence in the current period or in an earlier period, and that are held for sale, use in production or other use at a later date." (United Nations, 2014, 2025)

[4] The glossary definition of valuables reads: "Products of considerable value that are not used primarily for purposes of production or consumption but are held as a store of value over time." (United Nations, 2025)

[5] The glossary definition of consumption of fixed capital reads: "Consumption of fixed capital is the decline, during the course of the accounting period, in the current value of the stock of fixed assets owned and used by a producer as a result of physical deterioration, normal obsolescence or normal accidental damage." (United Nations, 2014, 2025)

[6] The glossary definition of value-added is: Contribution to the economy by a producer or an industry or an institutional sector, which is estimated by the total value of output produced and deducting the total value of intermediate consumption of goods and services used to produce that output.

>> Final consumption in IOA data --> Other source node/Other system outflow

The concept of final consumption appears in both monetary and physical SUTs and IOTs. In MSUTs and MIOTs, it represents consumption expenditure by final consumers on goods and services used for purposes other than economic production. Here, final consumers are generally categorized according to one of three subtypes: households, government, and non-profit institutions serving households (NPISH). The consumption of durable goods by final consumers is also recorded here, although this is often not differentiated from other types of final consumption (United Nations, 2018, 2025). For this reason, final consumption is not classified as a stock node/inflow in **Table 5.4** or **Table 5.5**.

In PSUTs and PIOTs, entries in the final consumption columns more broadly relate to material flows to and from final consumers. This includes both system outflows (e.g. consumption of final products) as well as system outflows (e.g. waste generation by final consumers) (United Nations, 2014, 2018).

5.2.2 Results of The Conceptual Mapping

This section presents the final conceptual mapping that is used for the initial assessment of terminological and conceptual alignment in **Section 5.3**. First, **Table 5.4** shows how method specific terminology is mapped to the method-neutral concepts of system boundary, resolution and balancing equations as defined in **Table 5.1**. Then, **Table 5.5** and **Table 5.6** present the conceptual mapping of method-specific concepts onto the method-neutral node and flow definitions presented in **Table 5.2** and **Table 5.3**.

Table 5.4: Conceptual mapping showing how method-specific concepts in MFA data, SUTs and IOTs relate to our method-neutral definitions of system boundary, disaggregation scheme and balancing equations (**Table 5.1**)

Note. Dashes (--) are used to list multiple method-specific terms that correspond to the same method-neutral concept. All subtypes of SUTs and IOTs are grouped in a single row, as these all implement the abovementioned concepts in similar ways**.

Data type	System boundary (discussed in Section 5.4.1)	Disaggregation scheme (discussed in Section 5.4.5)	Balancing equations (discussed in Section 5.4.2)
UPIOM (Myers et al., 2018)	System boundary: -- reference material -- reference timeframe -- reference space	Subsystem disaggregation: -- type of disaggregation -- level of disaggregation	Mass balance
General SEM data (Pauliuk, 2015)	Boundary of socioeconomic metabolism	Resolution	Balancing equation
Generic MFA data	System boundary: -- Spatial boundary -- Temporal boundary -- Other boundaries	Resolution	Mass balance
MSA data	System boundary: -- Spatial boundary -- Temporal boundary -- Other boundaries	-*	Mass balance
EW-MFA data	System boundary: -- Spatial boundary -- Temporal boundary -- Other boundaries	(level of) detail	Mass balance
IOA data (i.e. SUTs and IOTs)	-- Spatial boundary -- Temporal boundary -- Production boundary -- Asset boundary	-- Sectoral resolution -- Spatial resolution	-- Balance by product -- Balance by industry -- Balance across layers**

* the concept of disaggregation schemes is not directly referenced in the MSA methodology (Bio by Deloitte, 2015; Matos de Torres, 2020), but MSA data does disaggregate the economy in a number of lifecycle stages

** Balance across layers is only implemented in multilayer HSUTs & HIOTs. See also Section 5.4.3.

Table 5.5: Conceptual mapping showing how method-specific concepts in MFA data, SUTs and IOTs relate to our method-neutral definitions of nodes (**Table 5.2**)

Note. Dashes (--) are used to list multiple method-specific terms that correspond to the same method-neutral concept. HSUTs and HIOTs are excluded from this overview, as these simply combine elements of monetary and physical SUTs or IOTs.

Data type	Intermediate nodes			Source nodes			Sink nodes			Source or sink nodes
	Transformative node	Distributive node	Storage node*	Import node	Reserves node	Other source node	Export node	Dissipation node	Other sink node	Stock node
SEM data: Pauliuk et al. (2015)	Transformation process	Distribution process (or market)	Process with inventory/ stock	-**	Natural stocks	Agents (source factors of production)	-**	Natural stocks	-**	Stock
UPIOM: Myers et al. (2018)	Transformative process	Distributive process	Storage process	-**	-**	-**	-**	-**	-**	Stock
Generic MFA data	Process	Market process	Process with stock	Import process	-**	-	Export process	-**	-	Stock
MSA data	Process	Market stage	Process with stock	-**	Reserves	-	-**	-**	-	-- in-use stock -- end-of-life stock
EW-MFA data	Socio-economic production and consumption	-	-	-**	Natural environment	-**	-**	Natural environment	-**	Stock
MSUT	Industry (or sector)	Products	-	Imports	-	Value added (excl. CFC)	Exports	-	Final consumption: -- by households; -- by government; -- by NPISH	-- Gross Capital Formation; -- Consumption of Fixed Capital (CFC)
PSUT	Industry (or sector)	-- Products -- Residuals -- Natural Inputs	-	Imports	Environment	-	Exports	Environment	Final consumption: -- by households; -- by NPISH	-- Gross Capital Formation; -- Accumulation
MIOT	Industry (or sector)	-	-	Imports	-	Value added (excl. CFC)	Exports	-	Final consumption: -- by households; -- by government; -- by NPISH	-- Gross Capital Formation; -- Consumption of Fixed Capital (CFC)
PIOT	Industry (or sector)	-- Generation of Residuals -- Use of residuals	-	Imports	Environment	-	Exports	Environment	Final consumption: -- by households; -- by NPISH	-- Gross Capital Formation; -- Accumulation

*A storage node can simultaneously be a transformative or distributive node (e.g. when stocks are recorded directly within another process in MFA data). All other node types are mutually exclusive.

** These nodes are not explicitly present in the system structure of the described data type, but corresponding system inflows/outflow are (see **Table 5.4**).

Table 5.6: Conceptual mapping showing how method-specific concepts in MFA data, SUTs and IOTs relate to our method-neutral definitions of flows (**Table 5.3**)

Note. Dashes (--) are used to list multiple method-specific terms that correspond to the same method-neutral concept. HSUTs and HIOTs are excluded from this overview, as these simply combine elements of monetary and physical SUTs or IOTs.

Data type	Intermediate flows	Source nodes				Sink nodes			
		Import flow	(Net) stock outflow	Extraction	other system inflows	Export flows	(Net) stock inflow	Emissions	other system outflows
SEM data: Pauliuk et al. (2015)	Flow	Imports	Net stock addition	Use of Natural resources	Factor use	Exports	Net stock addition	Emissions	-
UPIOM: Myers et al. (2018)	Flow	Trade flow	Stock depletion	Cross-boundary flow	Cross-boundary flow	Trade flow	Stock accumulation	Cross-boundary flow	Cross-boundary flow
Generic MFA data	Flow	Imports	Stock depletion	Extraction	-	Exports	Stock accumulation	-	-
MSA data	Flow	Imports	-	Extraction	-	Exports	Annual addition to stock	-- In-use dissipation -- Output from value chain	-
EW-MFA data	Transformation incl. recycling	Imports	Net removals from stock	Domestic Material Extraction (DE)	Input balancing items	Exports	Net Additions to Stock (NAS)	Domestic Produced Output (DPO)	Output balancing items
MSUT	-- intermediate consumption -- product output	Imports	Consumption of Fixed Capital (CFC)	-	Value added (excl. CFC)	Exports	Gross Capital Formation (GCF)	-	Final consumption (excl. GCF)
PSUT	-- intermediate consumption -- product output -- generation of residuals by industry -- extraction of natural inputs -- collection and treatment of residuals	Imports	-- residuals from scrapping of produced assets -- residuals from final consumption	-- natural inputs from the environment -- residuals from the environment	-	Exports	-- Gross Capital Formation (GCF) -- Accumulation of residuals in landfill	Residual flows to the environment	-- Final consumption of products (excl. GCF) -- Final consumption of residuals
MIOT	intermediate consumption	Imports	Consumption of Fixed Capital (CFC)	-	Value added (excl. CFC)	Exports	Gross Capital Formation (GCF)	-	Final consumption (excl. GCF)
PIOT	-- intermediate consumption -- generation of residuals by industry -- collection and treatment of residuals	Imports	-- residuals from scrapping of produced assets -- residuals from final consumption	Natural inputs from environment	-	Exports	-- Gross Capital Formation (GCF) -- Accumulation of residuals in landfill	Residual flows to the environment	-- Final consumption of products (excl. GCF) -- Final consumption of residuals

5.3 Initial Assessment of Conceptual Alignment

In this section: The conceptual mapping tables presented in **Section 5.2** interpreted for an initial assessment of the terminological and conceptual alignment between MFA data, SUTs and IOTs, according to the procedure laid out in **Section 4.2.2**. First, **Section 5.3.1** identifies significant differences between data types, by highlighting conceptual elements that are present in one data type, but absent in others. Second, **Section 5.3.2** identifies cases of conflicting terminology, where similar terms may correspond to multiple concepts depending on the context. Lastly, **Section 5.3.3** highlights method-specific terms that correspond to the same method-neutral concepts, pointing towards aligned or possibly equivalent terminology. Whether these terms truly have identical interpretations is investigated in the closer conceptual comparison of **Section 5.4**.

5.3.1 Conceptual omissions

The conceptual alignment between data types is assessed by comparing individual cells within each column of the conceptual mapping tables presented in **Section 5.2**. If a cell is empty, the concept in question has no method-specific counterpart in the data type corresponding to the row. Such conceptual omissions are especially relevant to this thesis because they represent conceptual differences between data types.

>> *Source/sink nodes corresponding to system inflows/outflows often omitted in MFA data*

Table 5.5 and Table 5.6 show that system inflows and outflows are represented without a corresponding source or sink node in MSA data, EW-MFA data and most generic MFA data. This implies that only the destination and magnitude of system inflows flow are recorded, and for system outflows only the origin and magnitude are recorded. A possible explanation is that compilers of MFA data are mainly interested in what flows exit or enter the system of interest, not necessarily where to or where from. The latter may not even be known in many cases. Explicitly showing that the origin or destination of these flows is unknown adds little information.

That said, the lack of precise terms to refer to the destination or origin of flows crossing the system boundary makes it more difficult to discuss the underlying directed graph structure. Explicitly source and sink nodes as in our neutral conceptual framework or in the graph-based MFA model of Van der Voet et al. (1995) may improve conceptual clarity.

>> *Some subtypes of nodes and flows are omitted depending on the unit-of-account*

A more-or-less expected but nevertheless important finding from **Table 5.4** and **Table 5.5** is that the types of nodes and flows recorded in each data type are strongly related to the unit of account that is used. Most importantly, monetary accounts (MSUTs and MIOTs) do not record information on environmental emissions and residuals without monetary value, unless extended with satellite accounts expressed in physical units (e.g. EE-MIOTs and EE-MSUTs). Seeing this, it could be said that the unit-of-account makes up a crucial part of the system boundary, in the sense that it largely defines which flows are and are not recorded within the dataset. This idea is further developed in Section 5.4.1.

>> *Stocks never modeled as intermediate nodes in IOA data*

Looking at the storage node column of **Table 5.4** makes clear that stocks in IOA data are never modeled as intermediate nodes. Instead, stocks are exclusively modeled using stock nodes that act as sources and sinks. In other words, stocks in IOA data are only modeled to the extent that they exchange flows with intermediate nodes (i.e. sectors/industries) within the system boundary. This idea is explored further in Section 5.4.4

5.3.2 Conflicting Terminology

As described in **Section 4.2.2**, conflicting terminology is identified by looking for identical or similar-sounding terms in the conceptual mapping tables of Section 5.2. If such terms appear in different columns, their definition is not unique to a single concept, and their interpretation may differ depending on the context. This may cause conceptual confusion and potentially obstruct comparison and integration between data types.

>> *No substantial terminological conflicts between MFA data, SUTs and IOTs*

In the conceptual mapping tables of **Section 5.2** there are no examples of similar-sounding method-specific terms that are mapped to different method-neutral definitions^[1]. In other words, similar terms generally refer to the same general concepts. As such, using method-specific terminology outside their original context is not likely to cause significant misinterpretation. This speaks to the prospects of terminological harmonization across methods, although nuanced differences that aren't captured in the method-neutral definitions of **Section 5.2** may still need to be overcome. This is further investigated in **Section 5.4**.

>> *Distinction between nodes and flows is unclear within IOA terminology*

Comparing **Table 5.4** and **Table 5.5** shows the distinction between nodes and flows is generally well-reflected in MFA terminology. Looking past the lack of source/sink nodes corresponding to system inflows/outflows described in **Section 5.3.1**, distinct terms are used for nodes and flows.

By contrast, SUTs and IOTs mostly use the same terms to describe system inflows/outflows and their corresponding source/sink nodes. Specifically for Imports, Exports, Consumption of Fixed Capital, Gross Capital Formation, Value added and Final Consumption. These terms are used to refer to distinct flows within IOTs and SUTs (See **Table 5.5**). Confusingly, the same terms also denote the column indices representing the origin or destination nodes of these flows (See **Table 5.4**). Only when broken down into subcomponents^[2] do these terms used in the column indices of SUTs and IOTs start to resemble subcomponents of the economy that could be interpreted as nodes (i.e. the origin or destination of a flow). As a result, the terminological distinction between flows and nodes is not always clear in IOA data.

Admittedly, the distinction between nodes and flows is very clear when SUTs and IOTs are presented visually in a conventional tabular format or Sankey diagram. However, when discussing the structure of these data types in writing, the lack of terminological distinction between nodes and flows may lead to confusion. This ambiguity may make it more difficult to use directed graph terminology to bridge the terminological differences between MFA data and IOA data.

5.3.3 Comparable Concepts and Aligned Terminology

To assess which method-specific terms refer to similar concepts, each column of the conceptual mapping tables of **Section 5.2** is evaluated. All entries within a single column roughly correspond to the same concept, although nuanced differences in their interpretation may not be captured by our neutral conceptual framework. As such, the closer conceptual comparison of **Section 5.4** is essential to assess the full conceptual alignment between these comparable concepts.

>> *Terminological alignment within MFA and IOA*

When comparing the method-specific terms used for single method-neutral concepts in **Table 5.4** and **Table 5.5**, an interesting pattern emerges. Within the family of MFA data, more-or-less identical (or at least similar) terms are used to refer to the same concept. The same goes for terms used within the field of IOA to describe the structure of SUTs and IOTs. This is unsurprising, and points towards terminological conventions that are shared throughout the broad fields of MFA and IOA.

>> *Little terminological alignment between MFA and IOA*

Much different is the terminological alignment between MFA data and IOA data: in **Table 5.4** and **Table 5.5** there are few examples where terms used in MFA data are similar to those used for SUTs and IOTs. The only true examples of aligned terminology are imports and exports, which have the same meaning across all methods. All-in-all, it can be concluded that the terminology used to define the structure of MFA data, SUTs and IOTs varies significantly, even if the underlying model elements are structurally and conceptually similar.

[1]The one exception is that the 'extraction of natural inputs' serves as an intermediate flow within the structure of conventional PSUTs, while the similar-sounding 'natural inputs from the environment' is classified as an extraction flow in both PSUTs and PIOTs. That said, both terms refer to the same concept: the extraction of natural resources from the environment. The use of two separate terms simply reflects the fact that resource extraction is recorded twice within a conventional PSUT structure. Hence, conceptual confusion is unlikely.

[2]e.g. imports and exports by region, final consumption by households/government/NPISH, Gross Capital Formation by asset category

>> IOA terminology is more conceptually specific than MFA terminology

Another interesting finding of **Table 5.4** and **Table 5.5** is that SUT and IOT terminology often has a great variety of distinct terms corresponding to a single method-neutral concept, whereas MFA terminology often only has one or two. For example, intermediate flows in MFA are referred to simply as flows, whereas PSUT and PIOT terminology distinguish between various types of product, residual, and natural input flows.

Firstly, this indicates that our method-neutral definitions are too general to capture all nuanced conceptual distinctions in SUTs and IOTs. As discussed in **Section 4.2**, this was expected and is exactly why a closer conceptual comparison follows this initial assessment of terminological and conceptual alignment. Even so, the often one-to-one correspondence between MFA-specific terms and method-neutral concepts suggests that our method-neutral framework does capture most of the conceptual distinctions made in conventional MFA terminology. It thus seems that the terminology used in IOA is more conceptually specific than MFA terminology. It could be said that SUTs and IOTs generally conveys more qualitative information on nodes and flows than conventional MFA data. However, it should be noted that the level of conceptual specificity is closely related to the level of conceptual disaggregation (i.e. resolution), which **Section 5.4.5** shows to be purely convention-bound and easily reconcilable.

>> Seemingly comparable concepts that demand closer conceptual comparison

While the terminology used differs significantly between MFA data and IOA data, **Table 5.4** and **Table 5.5** show that the method-neutral concepts they refer to are largely the same. Of course, any seeming conceptual overlap could be attributed to insufficiently specific method-neutral definitions that are unable to capture important nuances in interpretation. Therefore, **Section 5.4** investigates to what extent these seemingly equivalent terms truly have the same interpretation. That said, key instances of seeming conceptual overlap are:

- (i) Various terms in MFA data, SUTs and IOTs that correspond to our method-neutral concept of system boundary (closer comparison follows in **Section 5.4.1**).
- (ii) Processes in MFA data and sectors or industries in SUTs and IOTs, all of which correspond to our method-neutral concept of transformative nodes (closer comparison follows in **Section 5.4.2**).
- (iii) Markets in MFA and implicit distributive nodes for residuals and/or products in SUTs and IOTs, which both correspond to our method-neutral concept of distributive nodes (closer comparison follows in **Section 5.4.2**).
- (iv) Various balance-related terms in MFA data, SUTs and IOTs that correspond to our method-neutral concept of balancing equations (closer comparison follows in **Section 5.4.3**).
- (v) Stocks in MFA data and capital in SUTs and IOTs, both of which relate to our method-neutral concepts of stock nodes, stock inflows and/or stock outflows (closer comparison follows in **Section 5.4.4**).
- (vi) A variety of terms in MFA data, SUTs and IOTs that all correspond to our method-neutral concept of disaggregation scheme (closer comparison follows in **Section 5.4.5**).

5.4 Closer Conceptual Comparison

In this section: The seemingly comparable method-specific concepts found in **Section 5.3.3** are further investigated. This closer conceptual comparison aims to determine to what extent their interpretation is truly the same, and to assess whether any identified differences in interpretation are convention-bound or irreconcilable. To support this comparison and improve understanding of the both similarities and differences between data types, this section also provides conceptual clarification from a method-neutral perspective.

The closer conceptual comparison is structured according to five overarching concepts. First, **Section 5.4.1** compares how system boundaries are implemented across data types. Then, **Section 5.4.2** and **Section 5.4.3** respectively discuss the interpretation of intermediate nodes and the implementation of balancing equations. **Section 5.4.4** investigates how stocks and capital are represented differently in MFA and IOA. Lastly, **Section 5.4.5** provides clarification on the way disaggregation schemes are implemented in each data type. Those only interested in the most relevant takeaways can skip to **Section 6.1**, where important results of this chapter are synthesized and condensed into a smaller number of key findings.

5.4.1 Implementation of System boundary

The initial conceptual comparison of Section 5.3.3 highlighted that a variety of different method-specific concepts correspond to our general method-neutral concept of system boundary. By critically comparing these method-specific implementations of system boundaries, five unique boundary criteria were identified: (i) reference period, (ii) reference region, (iii) economic boundary, (iv) unit-of-account, (v) reference material.

As summarized in **Table 5.9**, the first two of these are implemented similarly across all data types^[1], whereas the latter three are implemented differently, or not at all, depending on the data type. The remainder of this section focuses on articulating these differences. It should be noted however that system boundary definitions are convention-bound modeling choices, and choosing different system boundaries does not change the system structure of MFA data, SUTs or IOTs. If desired, all differences between data types described in this section could in principle be overcome by revising or adapting system boundary definitions.

Table 5.7: Comparison showing how five shared system boundary criteria are implemented differently across data types.

Data type	Reference period (temporal boundary)	Reference region (spatial boundary)	Economic boundary	Unit-of-account	Reference material (if material-specific)
Generic MFA data	Single year	Any geographic region	Optional	Bulk mass or material-specific mass	Any substance or material group
EW-MFA data	Single year	National economic territory	Full economy defined by SNA/SEEA, with slight adaptations	Material-specific mass	Predefined set of major material groups (e.g. biomass, metals)
MSA data	Single year	EU geographic territory	Predefined set of production stages covering the full economy	Material-specific mass	Any substance or material group
MSUT/ MIOT	Single year	National economic territory/territories	Productive economy as defined in SNA	Monetary value	Any substance or material group
PSUT/ PIOT	Single year	National economic territory/territories	Productive economy defined in SNA/SEEA	Bulk mass, material-specific mass, or energy	Any substance or material group
HSUT/ HIOT	Single year	National economic territory/territories	Productive economy defined in SNA/SEEA	Any combination of units	Any substance or material group

[1] These similarities are further commented on in Appendix C

>> *Difference: Definition of economic boundaries varies between data types*

SUTs and IOTs exclusively record flows to, from and within the productive economy as defined in the SNA (UNEP, 2023; United Nations, 2018, 2025). In the SNA and SEEA, the economy is demarcated by five mutually exclusive sub-systems: the so-called institutional sectors which collectively make up the full economy^[1] (United Nations, 2025). Within this boundary, the productive economy is distinguished from the non-productive economy through the production boundary (United Nations, 2025). Notably, most flows that occur after final consumption by households are excluded by this production boundary (see Section 5.4.3).

By contrast, EW-MFA takes the full economy as the system of interest, including productive activities but also consumption and accumulation. Its definition of the full economy is closely aligned SNA and SEEA, but excludes some aspects of agricultural production^[2] (UNEP, 2023; United Nations, 2014, 2018, 2025).

MSA data takes a more bottom-up approach. Instead of explicitly defining the boundaries of the economy, it defines each relevant process and flow that should be recorded within its system boundary. The included processes cover material extraction, processing, manufacturing, consumption, accumulation and waste treatment/recycling (BIO by Deloitte, 2015; Torres de Matos, 2020). Seeing this, it can be said that MSA data more-or-less covers the full economy, although not the SNA definition thereof.

In generic MFA data, neither need nor custom require an exclusive focus on economic processes and flows. Often, no explicit economic boundary is defined, allowing for the inclusion of both economic and non-economic material flows such as biochemical or geophysical cycles (Baccini & Brunner, 2012; Brunner & Rechberger, 2017).

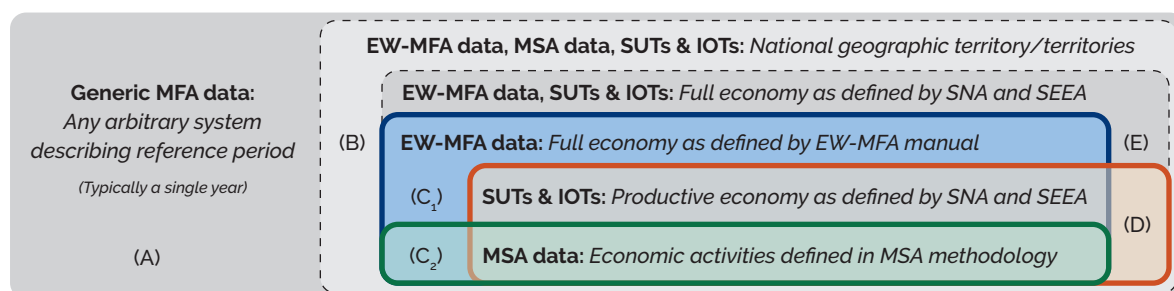


Figure 5.3: The overlap and differences between various definitions of the economic boundary.

Note. (A) Boundaries that are inconsistent with national territorial borders; (B) Non-economic elements such as environmental compartments; (C) Non-productive elements of the economy such as in-use consumer stocks; (D) Misalignment between the SNA and EW-MFA definition of the productive economy. For example with respect to agriculture; (E) Other potential misalignment between the SNA and EW-MFA definition of the full economy, although no concrete examples of this were found.

>> *Difference: Each unit-of-account necessarily prevents some flows from being recorded*

As observed in Section 5.3.3, the unit in which different subtypes of MFA data, SUTs or IOTs are expressed largely determines which flows can and cannot be recorded, because not all transactions can be described in every unit (e.g. services cannot be expressed in mass units and environmental emissions are difficult to express in monetary terms). This makes it an important but understated element of the system boundary definition. In the SNA, the unit in which transactions between sectors are recorded is referred to as the unit of account and reference unit (United Nations, 2025). The former term will be adopted throughout this thesis.

As visualized in **Figure 5.4** the unit-of-account is a defining characteristic that separates different subtypes of SUTs, IOTs and MFA data: MSUTs/MIOTs are always expressed in a unit of currency, while the unit of account of PSUTs/PIOTs is either a unit of mass or energy (United Nations, 2014, 2018, 2025). The terms unit of account and reference unit are not familiar to MFA. However for all MFA data it is implied that flows are expressed in mass units (Brunner & Rechberger, 2017), similar to PSUTs/PIOTs.

[1] The five institutional sectors defined in United Nations, (2025) are: (i) non-financial corporations, (ii) financial corporations, (iii) general government, (iv) non-profit institutions serving households; (v) households

[2] UNEP (2023) notes: “There are some important differences between the SEEA and the system boundaries of EW-MFA which are especially important in the domain of agriculture, where the SEEA conceptualises agricultural area and plants as part of the economy (cultivated biological resources) and EW-MFA as part of the environment. Consequently, the SEEA treats water, carbon dioxide, and nutrients as a natural input whereas EW-MFA interprets the harvest of crops as natural input.”

SUTs and HIOTs use multiple units of account, allowing them to simultaneously record different flows that cannot be expressed in the same unit (see Figure 5.2). Single-layer HSUTs/HIOTs record each flow only once, although different flows may be expressed in different characteristic units (e.g. tangible goods in mass units, services in currency units) (Hawkins et al., 2007; Miller & Blair, 2021). Multi-layer HSUTs/HIOTs such as those created by Merciai & Schmidt (2012) and Merciai (2019) use a different unit of account in each layer, in which all flows are recorded that can be expressed in said unit of account. In this sense, it could be said that HSUTs/HIOTs are made up of multiple single-layer SUTs/IOTs describing the same system of interest but in a different unit-of-account. By recording multiple aspects of the same flow, multi-layer accounts give more comprehensive accounts than any single SUT/IOT can.

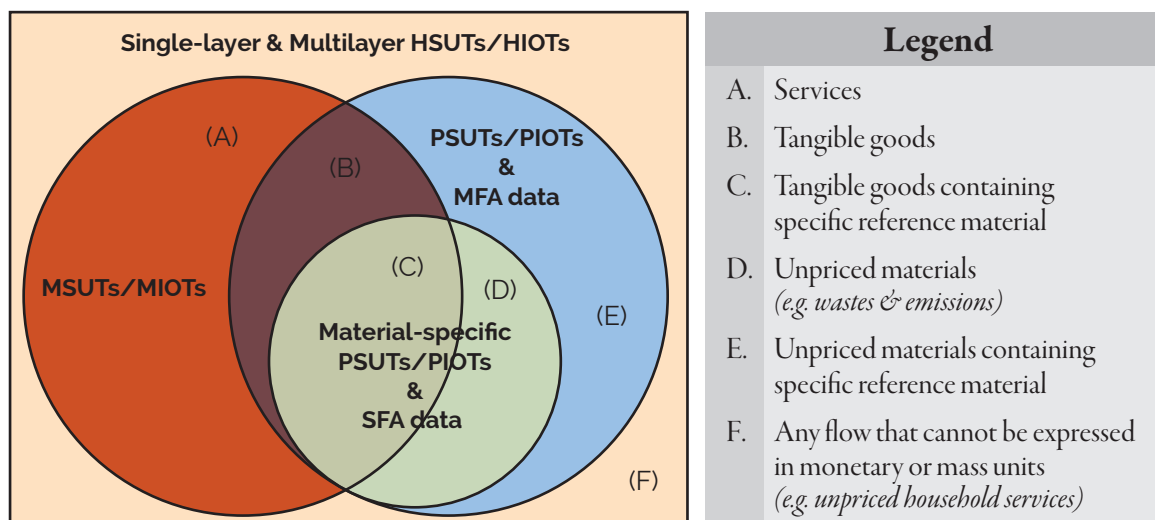


Figure 5.4: Schematic overview showing the overlap and differences between different units-of-account.

>> Difference: Some physical accounts are material-specific, while others are not

When speaking of mass as a unit of account, some disambiguation is required. Physical accounts may either record the aggregate material flows without taking into account their composition, or they may focus on a specific reference material^[1]. Either approach is paired with different units-of-account, as described below.

In MFA, simply recording aggregate material flows without distinguishing between material types is referred to as bulk-MFA (Brunner & Rechberger, 2017). The type of unit-of-account corresponding to this approach is thus referred to in Table 5.9 bulk mass, expressed in units as kg/year and tonne/year. Conventional PIOTs and PSUTs are also expressed in such bulk mass units, and do not distinguish between material types (United Nations, 2014).

Datasets which record only the mass flow of a specific reference material within bulk material flows use units of account such as 'ktCO₂ per year' or 'kg plastic per year'. In Table 5.9 these data types are said to use material-specific mass as a unit of account. Many MFA datasets fall within this category, in which case they are sometimes referred to Substance Flow Analysis (SFA) data (Brunner & Rechberger, 2017). While the compilation of material-specific PSUTs and PIOTs has been proposed (e.g. Hoekstra, 2010 and Singh et al., 2017), these find no mention in the SEEA or SNA as of yet (United Nations, 2014, 2018, 2025).

5.4.2 Interpretation of intermediate nodes

As discussed in Section 5.3.2, processes in MFA data and sectors/industries in SUTs and IOTs both correspond to our method-neutral concept of transformative nodes. Similarly, markets in MFA data and the (implicit) markets for products and residuals in IOA are both modeled as distributive nodes.

This section presents a closer conceptual comparison of these concepts to assess the extent to which their interpretation is truly equivalent. In short, it was found that beyond the real-world activity these two subtypes of intermediate nodes represent, transformative nodes and distributive nodes are found to be practically equivalent, as they all represent black-box processes with balanced inflows and outflows. However, notable differences were found when comparing how the inflows and outflows of multi-output processes are typically recorded in conventional MFA data, SUTs and IOTs.

[1] This term is taken from Myers et al. (2018)

>> **Clarification: All intermediate nodes are black-boxes with balanced Inflows and outflows**

For all practical purposes, the interpretation of intermediate nodes is identical across all analyzed data types. They are modeled as black-box processes of which only the inflows and outflows are of interest, while internal mechanisms are not explicitly modeled (Brunner & Rechberger, 2017; Nakamura & Kondo, 2009; Majeau-Bettez, 2016). This goes for transformative nodes, distributive nodes, storage nodes, and all method-specific implementations thereof. What distinguishes intermediate nodes in MFA data and IOA data from source and sink nodes is that they are subject to balancing equations (Brunner & Rechberger, 2017; United Nations, 2018). This is further discussed in Section 5.4.3.

>> **Clarification: Multi-outflow nodes may require subjective allocation when analyzing data**

As described in Chapter 1, material flow data is not only used for descriptive purposes, but also for analytical purposes such as origins analysis, scenario analysis and footprint analysis (Ayres & Ayres, 2002). To do so, the interdependence between different components of the economy is often modeled by establishing mathematical relationships between the inflows and outflows of each node. For example, Transfer Coefficients in MFA (Brunner & Rechberger, 2017) and technical coefficients in IOA (Miller & Blair, 2021). However, inferring these relationships from MFA datasets, SUTs and IOTs may be problematic for nodes that have multiple inflows and outflows, as this requires subjective allocation.

This thesis argues that the factors determining the need for such subjective allocation are similar across all data types: analytical purpose and the number of inflows and outflows modeled to each node (see Figure 5.5). Both highly situational and not inherent to any specific data type. That said, the issue of subjective allocation indirectly relates to differences between methods, as discussed in later subsections. But first, additional clarification is given on Figure 5.5.

The problem with multi-output and multi-input processes has been mostly discussed in the context of Life Cycle Assessment (LCA), where it is often referred to as the ‘allocation problem’ (e.g. Heijungs & Frischknecht, 1998). It occurs when a modeled process provides more than one valuable function, which makes it impossible to infer a unique mathematical relationship between each functional flow and its associated inputs, emissions, wastes and environmental burdens. Attributing responsibility for these non-functional flows across multiple functional flows becomes a subjective modeling choice. This is problematic because it may significantly affect the outcome of an LCA study.

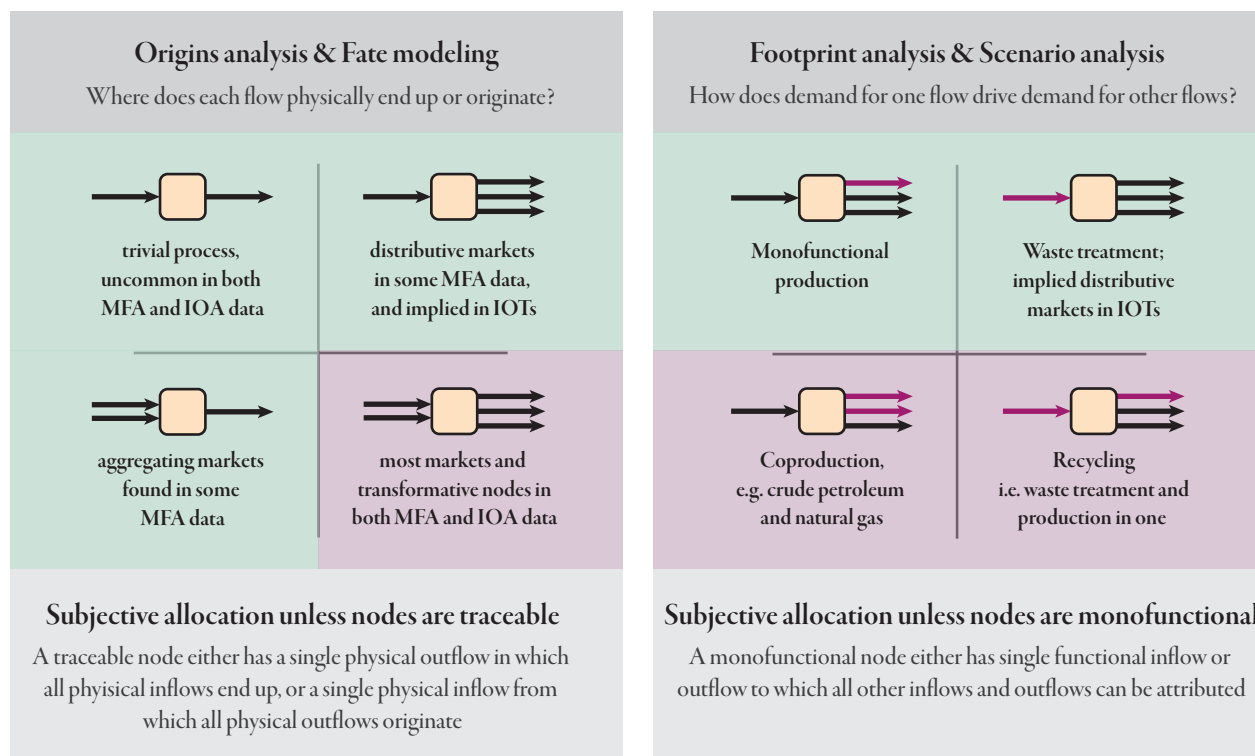


Figure 5.5: Examples showing when subjective allocation is needed for a given analytical purpose.

Note. In the examples for footprint analysis and scenario analysis, pink flows indicate functional flows. Examples marked in green represent nodes for which the relationship between flows can be established unambiguously, while those in red represent nodes for which subjective allocation is needed. Because the number of inflows and outflows that are modeled for each node are situational rather than data-type-dependent, the need for subjective allocation is not inherently associated with any data type

This thesis argues that this exact problem of subjective allocation does not only occur in LCA, but anytime when the relationships between flows need to be inferred from descriptive data for a multi-input and multi-output process. As illustrated in the remainder of this paragraph, this also includes footprint analyses and scenario analyses in IOA and origins analyses using MFA data, SUTs or IOTs.

Similar to LCA models, IOA models used for footprint analysis and scenario analysis (Ghosh, 1953; Leontief, 1954, 1970; Aiguilar-Hernandez, 2018; Miller & Blair, 2021) are often used to analyze the interdependence between sectors of the economy. In other words, how each economic activity indirectly drives other economic activities. To do so the input requirements of each sector must be attributed across its product outputs. Like in LCA, this requires subjective allocation unless each modeled sector is monofunctional (Majeau-Bettez et al., 2016). This requirement is one of the main reasons that SUTs are usually converted to IOTs before performing any analysis (Hoekstra, 2010; United Nations, 2018). This is elaborated under the next heading.

Another application of material flow datasets is to trace the physical origin and/or fate of materials, for example using static MFA models (Ayres & Ayres, 2002; Brunner & Rechberger, 2017). Here, it is not the attributional relationship between flows that is relevant, but rather the physical relationship between inflows and outflows that describes what material inputs physically end up in which outputs. Such relationships can only be unambiguously inferred from MFA data, SUTs or IOTs if nodes either have a single outflow in which all inflows must end up, or a single inflow from which all outflows must originate. If this is the case, these nodes may be considered traceable, a term borrowed from Majeau-Bettez et al. (2016).

>> Difference: IOTs require a one-to-one correspondence between products and sectors

As noted under the previous heading, IOA models require each modeled sector to be monofunctional in the sense that they produce a single product output to which all other flows can be attributed. For this reason, IOTs generally assume a one-to-one correspondence between sectors and products. In practice, this implies that each intermediate outflow of a sector represents the same homogenous product mix that is assumed to be produced using the same 'technological recipe' (Miller & Blair, 2021; United Nations, 2018). Other outflows such as residuals and natural input flows can only be recorded as system outflows. To understand how this ensures monofunctionality, each IOT sector can be interpreted as a combination of two monofunctional processes: a transformative node and an implicit distributive node for its single homogenous product output (Pauliuk, 2015a; Meyer, 2018). This is visualized in **Figure 5.6**.

While a one-to-one correspondence between products and sectors is useful from a modeling perspective, it is generally a misrepresentation of reality. Real-life economic activities often produce multiple very distinct products or services, which cannot be unproblematically represented by a single homogenous product mix. As a result, the descriptive accuracy of IOTs is limited compared to SUTs^[1] and MFA data, which do allow multiple product outputs to be recorded for a single sector.

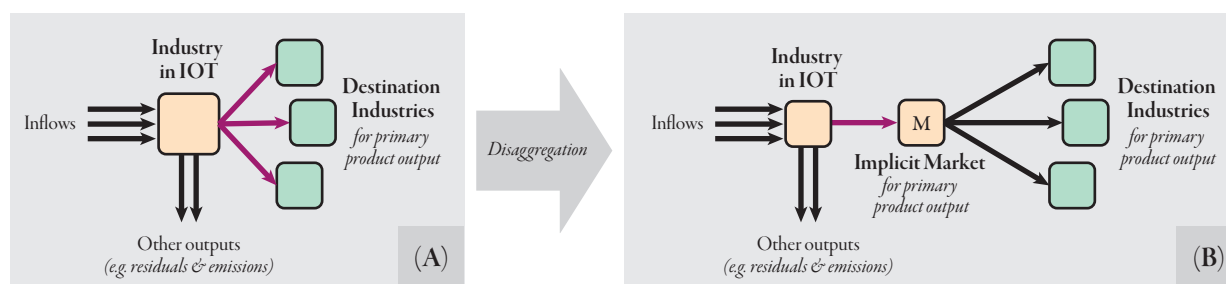


Figure 5.6: Implicit markets included in IOTs due to one-to-one correspondence between products and industries.

Note. Figure shows two alternative interpretations of a generic IOT industry, using the visual language defined in **Figure 5.1**.

(A) conventional interpretation: single transformative node with multiple product outputs to various destination sectors;
 (B) alternative interpretation: a combination of a transformative node producing a single primary product output (in purple), and an implicit single-inflow distributive node that distributes this primary product output across its destination sectors.

[1] The conventional way to construct IOTs is by first compiling SUTs and then converting these to IOTs using allocation constructs that guarantee monofunctionality for all sectors. These constructs often involve the aggregation of different product outputs, leading to a loss of information on the origin, destination and magnitude of individual product flows compared to the original SUT (United Nations, 2018; Majeau-Bettez et al., 2014).

>> Difference: Typical degree of traceability varies between data types

The traceability criteria presented in **Figure 5.5** make it possible to assess to what extent the typical structure of conventional MFA data, SUTs and IOTs allows flows to be traced from their origin to destination without needing subjective allocation. As stated in **Figure 5.5**, a node is traceable if it either has a single inflow from which all outflows originate, or a single outflow in which all inflows end up.

It is evident that most transformative processes modeled in MFA data and SUTs and IOTs do not fulfill this condition, as they typically transform multiple inputs into multiple products, byproducts and wastes/residuals. As a result, subjective allocation is always needed to model which physical inflows end up in which outputs. In this sense, no MFA dataset, SUT or IOT is truly fully traceable.

Distributive markets that aggregate inflows from multiple origins and redistribute these to multiple destinations are also not traceable. All markets defined in MSA data are of this type (Torres de Matos et al. 2020). The same goes for the (implicit) markets for residuals and/or products in conventional SUTs, and the markets for residuals in conventional PIOTs and HIOTs. After all, every residual or product recorded in these tables is typically produced by more than one sector and consumed by more than one sector (United Nations, 2018). By contrast, distributive markets in some generic MFA datasets are traceable. For example, Müller et al. (2006) and Meylan & Reck (2017) only include markets that aggregate domestically produced products and imported products into single product outflow. However, this simplicity can largely be attributed to the low sectoral and product resolution of these datasets.

The link between aggregation and traceability is illustrated by Majeau-Bettez et al. (2016). They show in the context of SUTs that traceability can be guaranteed by disaggregating datasets until each distributive node corresponds to a unique output of a transformative node. An example of this is shown in **Figure 5.7**. In principle, such disaggregation is possible for any distributive node regardless of the data type, as long as sufficiently detailed input data is available. This means that the level of traceability of a dataset is convention-bound and varies on a case-by-case basis.

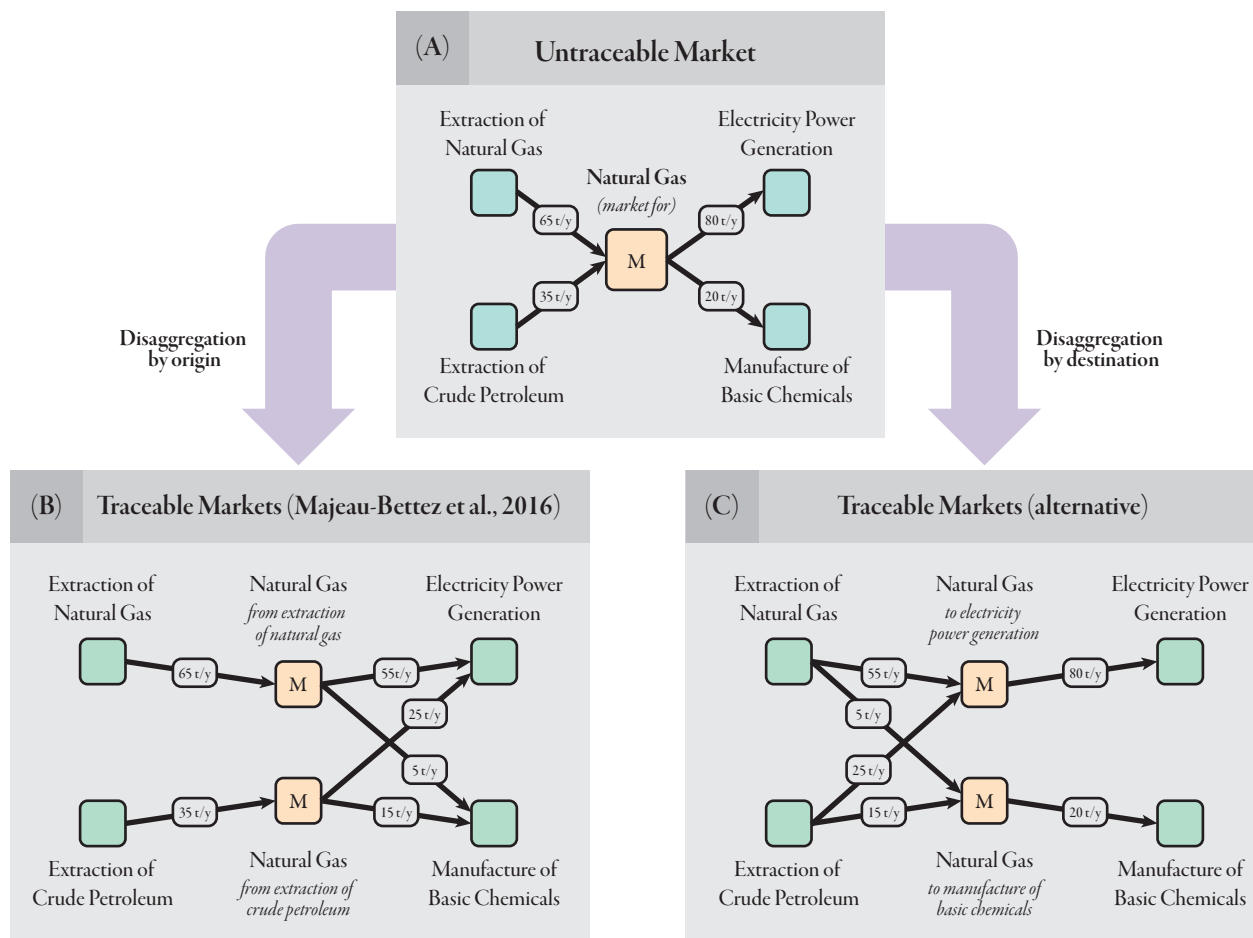


Figure 5.7: Example showing how disaggregation into sub-markets can ensure traceability of distributive nodes.

Note. This figure shows that differences in traceability are convention-bound, using the visual language of **Figure 5.1**.

(A) the origin of natural gas inflows to electricity power generation and manufacture of basic chemicals cannot be determined without subjective allocation; (B) each flow is traceable back to a single origin; (C) each flow is traceable to a single destination.

5.4.3 Implementation of balancing equations

As indicated in Section 5.3.2, all subtypes of MFA data, SUTs and IOTs adhere to balancing equations in one form or another. These are especially important in large datasets that involve bookkeeping data from a variety of statistical data sources, which are not necessarily consistent with each other. To ensure internal consistency in the final dataset, bookkept MFA data, SUTs and IOTs typically undergo some form of balancing procedure before being published (Brunner & Rechberger, 2017; United Nations, 2018, 2025). This section compares which balancing equations ‘conventional’ MFA data, SUTs and IOTs must adhere to after balancing. The results of this comparison are summarized in **Table 5.10**. Comparing the balancing procedures that are used to convert unbalanced bookkept datasets to balanced ones is left to further research.

Table 5.8: Overview comparing what balancing equations are implemented in each data type.

Characteristic	generic MFA data	EW-MFA data	MSA data	MSUT/MIOT	PSUT/PIOT	Single layer HSUT/HIOT	Multilayer HSUT/HIOT
Balanced property (= unit-of-account)	mass	mass	mass	monetary value	mass or energy	single property per row	single property per layer
Balance by product (= Eq 5.1)	✓	✓	✓	✓	✓	✓	✓
Balance by industry (= Eq 5.2)	✓	✓	✓	✓	✓		✓
General balance by node (= Eq 5.3)	✓	✓	✓				✓
Balance between layers (= Eq 5.4)			✓				✓

>> Clarification: Balance by Product and Balance by Industry

In the context of SUTs and IOTs, balance principles are applied in two distinct ways: balance by product and balance by industry (United Nations, 2018). The former implies that the total supply of each product, residual or natural input must equal its total use (Eq 5.1), while the latter implies that total inflows to each industry must equal its total output (Eq 5.2). Because each product, residual and natural input rows of SUTs and IOTs can be interpreted as distributive nodes, this essentially means that the inflows and outflows of every intermediate node in SUTs and IOTs must be balanced (Eq 5.3).

Analogous to the balance by industry in IOA, the principle of mass balance in MFA data states that mass inflows to each process must equal mass outflows plus net stock accumulation (Eq 5.3) (Brunner & Rechberger, 2017). Mass balance by product is also guaranteed, because the supply of each flow per definition equals use: Because flows must have both an origin and destination, each node outflow in MFA data is necessarily an inflow to another process or stock. This means that MFA data, PIOTs and PSUTs are equivalent in the sense that they are both mass balanced by product and mass balanced by industry.

Eq 5.1 **Balance by product:**

$$\sum \text{supply}_{\text{row}} = \sum \text{use}_{\text{row}} \quad \text{for every product, residuals and natural input row (i.e. implicit distributive node)}$$

Eq 5.2 **Balance by industry:**

$$\sum \text{inflow}_{\text{industry}} = \sum \text{outflow}_{\text{industry}} \quad \text{for every industry (i.e. transformative node)}$$

Eq 5.3 **General balance by node: (= balance by product & balance by industry)**

$$\sum \text{inflow}_{\text{node}} = \sum \text{outflow}_{\text{node}} + \Delta \text{stock} \quad \text{for every intermediate node}$$

>> *Difference: Interpretation of balance principles varies depending on unit-of-account*

As with many other differences between MFA data, SUTs and IOTs, the unit-of-account (see Section 5.4.1) plays a crucial role in determining how balance principles are implemented. MSUTs and MIOTs record flows in monetary units, and are balanced based on the circular flow of income principle. This states that the total monetary value of products must be conserved (United Nations, 2018, 2025). In other words, monetary value cannot be created or destroyed within the described system. Conversely, accounts expressed in mass units (i.e. MFA data, PSUTs and PIOTs) are balanced according to the conservation of mass principle, which states that mass must be conserved (Brunner & Rechberger, 2017; United Nations, 2014, 2018). Single-layer and multi-layer HSUTs or HIOTs may be balanced according to any other conservative property (e.g. embodied energy or carbon content), depending on the unit(s) of account which flows are expressed in (Hawkins, 2007; Merciai & Schmidt, 2012; Merciai, 2019). To minimize confusion it is wise to include the unit-of-account in the naming of balancing equations (e.g. 'balance by industry in mass units' or 'balance by product in monetary units'), especially in multilayer accounting (Pauliuk et al., 2015).

It should be emphasized that balance in one unit of account does not automatically imply balance in all units of account. Weisz & Duchin (2006) and Merciai & Heijungs (2014) both point out that in the context of MIOTs, balance in monetary units only implies an underlying balance in physical units if prices are homogenous for each product output (i.e. the price of a sector's product output is independent of the destination sector). Expressed in more general terms, balance in one unit of account only implies an underlying balance in another unit of account if the conversion factor between these units-of-account is homogenous for every flow type. In practice however, conversion factors are often inhomogeneous due to factors like imperfect competition or the aggregation of multiple non-homogeneous products within a single flow type.

Because balances in different units-of-account are not equivalent, one should be cautious when converting MFA data, SUTs or IOTs to different units. De Koning et al., (2015) and Majeau-Bettez et al. (2016) have confirmed that unit conversion can lead to biases and/or imbalances in the converted accounts, although not necessarily.

>> *Difference: Single-layer HSUTs and HIOTs do not guarantee balance by industry*

The defining characteristic of single-layer HSUTs and HIOTs is that different rows (i.e. products, residuals or natural inputs) are expressed in different units-of-account (e.g. currency for goods and service flows, mass for residual flows) (United Nations, 2018). This has no effect on the balance by product, as the total supply and total use of a given product, residual or natural input are expressed in the same unit of account. The same is not true for the inputs and outputs to a given industry. Because industry inputs and outputs may be expressed in different units of account, they cannot be compared and the balance by industry cannot be guaranteed.

>> *Difference: Multilayer HSUTs and HIOTs guarantee balance within and between layers*

Multilayer HSUT or HIOT use a single unit of account per layer to record all flows whose magnitude is expressible in said unit (Merciai & Schmidt, 2018; Merciai, 2019). This means that unlike single-layer HSUTs and HIOTs, the all inputs and outputs of each industry can be expressed in the same unit, meaning not only the balance by product but also the balance by industry can be guaranteed across multiple units of account.

The simultaneous accounting in multiple layers also creates the opportunity for balancing between layers (Eq 5.4), in which the relationship between different layers (expressed in different units) must be consistent with a corresponding matrix or vector of conversion factors (Merciai, 2019). This is one of the key strengths of multilayer HSUTs and HIOTs. As Hoekstra (2010) notes, having more balancing equations improves data quality by providing consistency criteria which can aid in the balancing process.

Eq 5.4 **Balance between layers:**

$$\text{Flow}^{\text{unit A}} \cdot \text{CF}^{\text{unit A} \rightarrow \text{unit B}} = \text{Flow}^{\text{unit B}} \quad \text{for every flow and conversion factor (CF)}$$

5.4.4 Interpretation of stocks and capital

Section 5.2.3 points out a conceptual overlap between stocks in MFA data and capital in SUTs and IOTs: both generally represent the accumulation of durable assets over time in (societal) stocks (Brunner & Rechberger, 2017; United Nations, 2015, 2025). Regardless of this conceptual similarity, a closer comparison finds that different data types focus on significantly different aspects of these stocks. **Figure 5.8** and **Table 5.11** summarize the results of this comparison.

Most importantly, only physical accounts can directly record stock magnitude and mutations in mass units, while monetary accounts only record (changes in) asset value. Also, conventional SUTs and IOTs do not record stock magnitude and stock changes, while also failing to exhaustively capture all stock inflows and outflows. Each of the aforementioned differences is further articulated in the remainder of this section.

Table 5.9: Comparison showing what characteristics of stocks are recorded by different data types.

Note. Multilayer HSUTs/HIOTs are omitted from this overview as they simply combine multiple single-unit SUTs/IOTs.

Characteristic	generic MFA data	EW-MFA data	MSA data	MSUT/MIOT	PSUT/PIOT	Single layer HSUT/HIOT
Recorded property (= unit-of-account)	Stock mass	Stock mass	Stock mass	Monetary asset value	Stock mass	Single property per stock inflow/outflow
Stock magnitude	Sometimes recorded	Sometimes recorded	Sometimes recorded	Not recorded	Not recorded	Not recorded
Stock inflow (see Table 5.5)	Any, generally exhaustive and may include balancing items	Those defined in EW-MFA, exhaustive if incl. balancing items	Those defined in MSA, not necessarily exhaustive	Only produced assets	Only produced assets	Only produced assets
Stock outflow (see Table 5.5)	Any, generally exhaustive and may include balancing items	Those defined in EW-MFA, exhaustive if incl. balancing items	Those defined in MSA, not necessarily exhaustive	Only consumption of fixed capital (=depreciation)	Only residuals used in production	Only consumption of fixed capital and residuals used in production
Net stock change	Always recorded	Always recorded	Not recorded	Not recorded	Not recorded	Not recorded

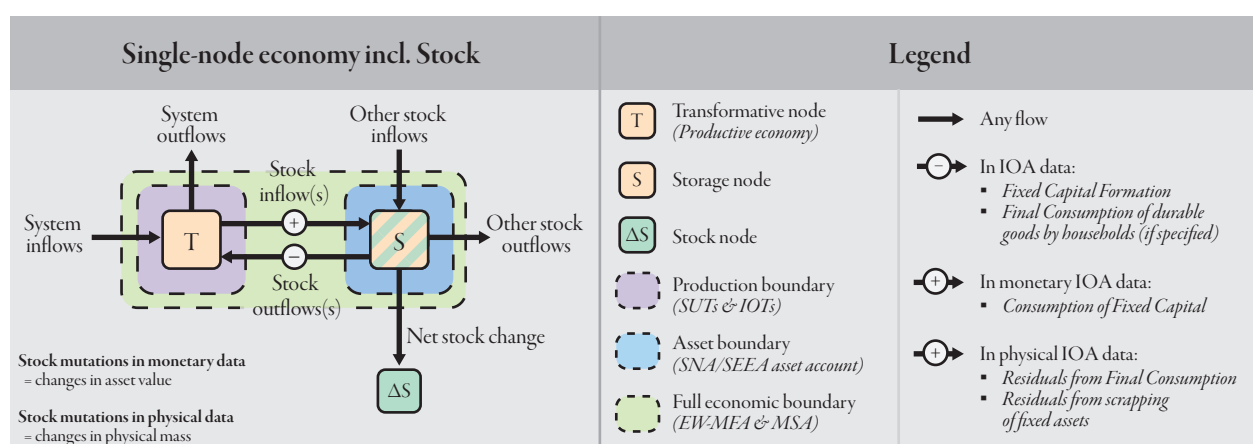


Figure 5.8: How stock mutations are recorded differently in depending on system boundary.

Note. Section 5.4.1 shows that EW-MFA data, MSA data and most generic MFA datasets cover the full economy, and can thus record all stock inflows and outflows, as well as net stock change. By contrast, unextended SUTs and IOTs can only record flows to and from the productive economy, meaning net stock change and some stock inflows and outflows cannot be captured. However, when combined with asset account of the SNA/SEEA, information on all stock mutations could still be communicated.

>> Clarification: The distinction and relationship between stock magnitude and stock mutations

An important point of clarification is the distinction between stock magnitude and stock mutations (i.e. stock inflows, stock outflows, and net stock changes). The former describes the total amount^[1] of material or value that has been accumulated in a stock at a given point in time, and is expressed as a quantity (e.g. tonne, euros). The latter are expressed as flows (e.g. tonne/year, euros/year) and describe changes of stock magnitude during the reference period of a dataset.

The relationship between these is especially relevant. As discussed in Section 5.5.2, the inflows, outflows and net stock changes must necessarily be balanced according to Eq 5.3/Eq 5.5, for stocks that are modeled as intermediate nodes (i.e. those with both inflows and outflows). Importantly, this balance requirement can only be met if all inflows and outflows to a stock are exhaustively recorded (Brunner & Rechberger, 2017; Graedel, 2019; UNEP, 2023).

Between stock magnitude and stock mutations there is also a direct mathematical relationship, at least when multiple subsequent reference periods are considered. Stock magnitude at the start of one reference period must necessarily equal stock magnitude at the beginning of the previous period plus net stock change over the preceding reference period (see Eq 5.6). This basic relationship underlies many dynamic analytic models in which MFA data and IOA data are used, such as dynamic MFA (Van der Voet et al., 2002; Müller et al. 2006), dynamic IOA (e.g. Leontief, 1953; Duchin & Szyld, 1985; Pan, 2006) and some Integrated Assessment Models (IAMs) (see Pauliuk et al., 2015b).

That said, the relationship described by Eq 5.5 is only meaningful when multiple reference periods are considered. Within individual single-period datasets, stock magnitude and stock mutations are independent values: stock mutations can be recorded without knowing stock magnitude, and stock magnitude can be recorded for a single point in time without knowing how it has mutated before, or will mutate after.

Eq 5.5 Relation between stock inflow, outflow and net stock change (adapted from Eq 5.3)

$$\sum \text{inflow}[t] = \sum \text{outflow}[t] + \Delta \text{magnitude}[t] \quad \text{for every stock node within any given timeframe } [t]$$

Eq 5.6 Relation between stock magnitude and net stock change in multi-period datasets

$$\text{magnitude}[t+1] = \text{magnitude}[t] + \Delta \text{magnitude}[t] \quad \text{for every stock node at any subsequent timesteps } [t] \text{ and } [t+1]$$

>> Difference: Physical accounts record physical stocks, monetary accounts record asset value

Yet again, the interpretation of the different datasets is largely dependent on their unit-of-account. MFA data, PSUTs and PIOTs record the physical magnitude, inflow, outflow, and/or stock changes in terms of mass units. On the contrary, stock magnitude in MSUTs and MIOTs is interpreted in terms of monetary asset value. Inflows, outflows and stock changes correspondingly represent mutations of this asset value. These may in some cases relate to changes in the physical stock volume (e.g. Gross Capital Formation), but may also represent other unrelated types of monetary appreciation or depreciation (e.g. Consumption of Fixed Capital; Revaluations).

The importance of this distinction has been highlighted before by e.g. Pauliuk et al. (2015b), Nakamura (2021). To illustrate, let us take the example of a single factory building. When interpreting the building as a physical stock, it may be described by a single inflow of materials at construction, followed by a long use period during which the stock magnitude stays constant and there are no stock inflows or outflows. Only at the end-of-life does the physical stock change again, at which point all accumulated materials simultaneously become a stock outflow and stock magnitude drops to zero.

Now consider the same building stock in terms of its asset value. The initial inflow and final outflow of asset value would coincide with the physical material inflows and outflows at construction and demolition, but their magnitude would not be directly correlated with the value of the physical materials. After all, the building's perceived value also depends on economic factors. The initial value of the stock would likely be significantly higher than its material value, and depreciate steadily throughout the building's use (e.g. because wear and tear diminish its potential to generate valuable services in the future). Other economic factors that are in no way related to the physical magnitude or quality of the stock (e.g. revaluations) may also cause fluctuations in the stock's value. All-in-all, this example shows that while monetary and physical accounts may describe the same stocks, the physical and monetary aspects of stocks are so loosely related that they are barely comparable.

[1] While stock magnitude is most often recorded as a total, it is sometimes disaggregated into separate subcomponents to communicate the composition of a stock (e.g. differentiated by age cohort or material type). While this has important implications for the practical applicability of MFA data and IOA data in dynamic models, this extra complexity is beyond the scope of this thesis. For those interested, Pauliuk et al. (2015b), OECD (2009) and Müller (2014) extensively discuss the topic of stock accounting in MFA and IOA.

>> *Difference: Unextended IOA data lacks space to record stock magnitude and stock changes*

MFA data contains designated spaces to record both net stock changes and stock magnitude. As shown in **Figure 5.2** of Section 5.1.2, these are typically presented side-by-side in a stock-box embedded within a process^[1]. That said, in practice many MFA datasets omit stock magnitude and only record net stock change (Myers et al., 2018; Graedel, 2019). This is possible because stock magnitude and stock mutations are independent in single-period datasets, as described above.

Like MFA data, conventional IOA data also records information on stock inflows and stock outflows (as shown in the conceptual mapping of Section 5.2). However, conventional SUTs and IOTs do not contain any space to record net stock changes, as pointed out in Section 5.3.3. The same goes for stock magnitude. That said, the SNA/SSEA does allow net stock changes and stock magnitude to be recorded in a separate account. The so-called asset account records the opening stock magnitude at the beginning of the reference period, stock inflows, stock outflows, and the closing stock magnitude at the end of the reference period (United Nations, 2014; see also Appendix C4). The structure of this asset account is closely aligned with the structure of SUTs and IOTs, sharing many of the same flows. After all, all stock inflows and outflows must be exhaustively recorded in the asset account to be able to determine net stock change.

This suggests that the omission of stock magnitude and net stock changes in IOA data could be addressed by extending conventional SUTs and IOTs with an asset account as satellite data. An example of this from the SEEA is presented in Appendix C4. However, generalizing this example to be applicable to any SUT or IOT likely requires further research, which is beyond the scope of this thesis. The key takeaway in the context of this thesis is that the omission of stock magnitude and net stock changes in IOA data can likely be overcome. In other words, it is convention-bound.

>> *Difference: IOA data only records stock mutations related to the productive economy*

Another difference between MFA data and IOA data is which stock inflows and stock outflows are recorded for any given stock. While there is no standardized way to record these in generic MFA data, and EW-MFA data and MSA data both define different stock inflows and outflows that should be recorded, all generally aim to record all inflows and outflows of each modeled stock (Brunner & Rechberger, 2017; Graedel, 2019; UNEP, 2023; Bio by Deloitte, 2015). This allows net stock changes to be computed as the difference between total stock inflows and total stock outflows (Eq 5.5). In the case of EW-MFA data and some generic MFA data, unspecified balancing items are sometimes used to guarantee stock mutations can be exhaustively recorded, even if these flows are not directly observed (Graedel, 2019; UNEP, 2023).

This is different in IOA data. As discussed in Section 5.4.1, the system boundary of conventional SUTs and IOTs is limited to the productive economy, as defined by the production boundary of the SNA. By consequence, stock inflows and stock outflows can only be recorded in these tables to the extent that they are produced or consumed by the productive economy. In practice, this means that only the accumulation of produced assets such as fixed capital, inventories and valuables can be recorded as stock inflow, whereas only Consumption of Fixed Capital and consumption residuals used or processed within the productive economy can be recorded as stock outflows (United Nations, 2014, 2025). Other stock mutations, such as losses from a stock directly to the environment, cannot be captured in non-extended SUTs and IOTs. As a result, it may in some cases be impossible to exhaustively record stock mutations, in turn making it impossible to determine net stock changes from conventional SUTs or IOTs.

However, as noted in the topic above, net stock changes are recorded in the asset account of the SNA/SEEA. This is possible because the asset account allows any stock inflow and outflow to be recorded, regardless of their relation to the production boundary of the SNA (United Nations, 2014). As such, the exclusive focus of conventional SUTs and IOTs on stock inflows from, and stock outflows to the productive economy can likely be overcome by extending them with an asset account that includes all other stock inflows and outflows, potentially by including balancing items as in EW-MFA and some generic MFA data.

[1] At least when presented visually in a Sankey diagram.

>> Difference: Most IOA data does not record the accumulation consumer durables

While the point above highlights that conventional SUTs and IOTs exclusively record the accumulation of produced assets as stock inflows, this does not imply that all stock formation of these produced assets is recorded in these tables. Because most SUTs and IOTs make no distinction between the final consumption of durable assets and the consumption of consumable goods (United Nations, 2018, See also Section 5.2.1), final consumption cannot typically be interpreted as a stock inflow. In turn, this makes that accumulation of in-use durable goods held by final consumers is not typically considered at all in IOA data.

However, this omission is purely convention-bound, as simply distinguishing between the final consumption of durable and non-durable goods in SUTs and IOTs allows the final consumption of durable goods to be interpreted as stock inflows into in-use stocks held by final consumers. This idea is already incorporated in the Handbook of SUTs and IOTs (United Nations, 2018), which suggests distinguishing between the final consumption of services, non-durable goods, semi-durable goods, and durable goods. That this is not often done in practice is likely the result of lacking data availability for such disaggregation.

However, convention-bound or not, the omission of in-use stocks in conventional SUTs and IOTs is a notable one. In-use stocks form the connection between the consumption of durable products (i.e. stock inflows) and waste flows or environmental emissions (i.e. stock outflows) that occur throughout those products' use phase and at their End-of-Life. For this reason, in-use consumer stocks are essential for circular economy monitoring and are included in both EW-MFA data (UNEP, 2023) and MSA data (Bio by Deloitte, 2015; Torres de Matos et al., 2020), as well as most generic MFA data (Graedel, 2019).

5.4.5 Implementation of disaggregation schemes

While the system boundary defines which system is described, it is the level of disaggregation that determines how much detail can be captured in MFA data, SUTs or IOT. Only by disaggregation into smaller subsystems (i.e. nodes) such as sectors and subsectors, can flows between these different parts of the economy be recorded (Myers et al., 2018; United Nations, 2025). While the exact disaggregation schemes used can vary significantly between datasets, some differences were nevertheless found when comparing methods. These differences are laid out within this section.

>> Clarification: Axes of disaggregation and level of disaggregation

To clarify the way various data types are disaggregated, Myers et al. (2018) distinguish between the type of disaggregation and the level of disaggregation (i.e. resolution). The former is used to denote along which lines nodes and flows are disaggregated^[1], whereas the second indicates how coarse or fine the disaggregation is along each of these axes. Because type of disaggregation is a somewhat non-descriptive term, this thesis adopts the term axes of disaggregation instead.

As noted by Myers et al. (2018), alignment between both the axes and level of disaggregation is a prerequisite for the equivalence between two datasets, regardless of the data type. That said, if the axes of disaggregation align, it is generally possible to reconcile differences in the level of disaggregation by re-aggregating the more disaggregated dataset until both the axes and level of disaggregation align (Myers et al., 2018). If the axes of disaggregation do not fully align, differences between datasets can only be reconciled if appropriate correspondence tables are available, or if divergent axes of disaggregation are fully aggregated away. (Myers et al., 2018)

>> Difference: Standardization of disaggregation schemes varies between methods

In generic MFA data, there are few established standards or conventions concerning the disaggregation of the system of interest into sub-processes. This has led to an overall lack of comparability between independently compiled MFA datasets, as also noted by others (e.g. Brunner & Rechberger, 2017; Myers et al., 2018; Graedel, 2019; Pauliuk, 2020).

By contrast, SUTs and IOTs conventionally rely on highly standardized classification schemes that may be selected from to disaggregate nodes and flows. Examples include: ISIC for economic activities/sectors; CPC for product types; AN codes for non-financial assets (United Nations, 2025). These classification schemes strictly prescribe axes of disaggregation, which may be implemented at multiple levels of coarseness. The actual level of disaggregation used in practice is left up to its compilers. They may opt for a coarse or fine resolution depending on factors as data availability and the intended purpose of the accounts.

[1] e.g. lifecycle stages, ISIC activities, CPC product types or AN asset codes

MSA data and EW-MFA data also follow strict conventions on disaggregation schemes. However, these do not align with the classification schemes used in SUTs and IOTs. For example, EW-MFA data may disaggregate material flows by product type or emission category, but the used classification system is not compatible with the CPC product classifications used in IOA (UNEP, 2023). Similarly MSA data disaggregates the economy by lifecycle stage (e.g. extraction, processing, manufacturing, use, collection and recycling) rather than ISIC-based economic activities (BIO by Deloitte, 2015).

>> *Difference: Typical axes of disaggregation vary between methods*

Choices about disaggregation are not strictly dictated by data type. Instead they are influenced by practical matters such as data availability and the intended purpose of a given dataset (Majeau-Bettez et al., 2016). As a result disaggregation is highly situational, and comparisons between methods are hard to generalize. To fully assess the alignment of disaggregation schemes between data types, an in-depth analysis on this specific topic would be needed. However, this is beyond the scope of this thesis.

That said, some correlation between data type and typical axes of disaggregation cannot be denied, even if these are largely convention-bound. As Myers et al. (2018) observe: SUTs and IOTs normally describe multiple materials in individual industries and product markets (i.e. not material specific), whereas MFA data typically describes a single material across a small number of products and industries (i.e. material specific). In other words, SUTs and IOTs typically disaggregate the economy into industries and markets by activity type and product type, but the description of flows between them remains highly aggregated. In contrast, MFA data tends to disaggregate flows by material type while keeping a more aggregated representation of the economy.

6 Discussion

Before moving on to interpretation, Section 6.1 recaps the most relevant results of Chapter 5. In Section 6.2, these findings are then used to answer the research questions defined in Chapter 3. Each answer includes a reflection on the limitations of the research methodology. Section 6.3 then discusses the implications of this thesis' findings on the potential role of MFA data, SUTs and IOTs in monitoring economic material flows and on the possible pathways for further methodological integration between MFA and IOA. Section 6.4 then reflects on the methods used and highlights limitations that may influence the interpretation of findings. Lastly, Section 6.5 proposes avenues for further research, which could drive the further methodological development and integration of MFA data, SUTs and IOTs.

6.1 Synthesis of Key Findings

In this Section: The findings of Chapter 5 are summarized and condensed into a number of key takeaways, spread across three general categories. First, Section 6.1.1 reflects on the terminological ambiguity that proves to form a significant obstacle to comparing MFA data, SUTs and IOTs. Then, Section 6.1.2 presents the key points of conceptual clarification that help better understand the system structure of the different data types. Lastly, Section 6.1.3 and Section 6.1.4 lay out the key differences between the analyzed data types. Here, the former discusses differences that seem irreconcilable, while the latter describes the convention-bound differences that could in principle be overcome by deviating from established methodological conventions.

6.1.1 Obstacles to Clear and Precise Methodological Discourse

A significant finding of this thesis is how difficult it is to write about MFA data, SUTs and IOTs at a meta-level, especially in a comparative context. Not only due to the complexity and abstractness of the topic, but also because terminological ambiguity undermines conceptual precision and easily leads to misunderstandings. After all, no analysis can be clear if the object of analysis cannot be clearly defined. The insights developed in this section are directly used to answer Subquestion 1 within Section 6.2

>> *Unclear distinction between data type, data collection and data analysis*

The first point of terminological ambiguity is that the term MFA is used more-or-less synonymously to describe a data type for storing information on material flows, a methodology for collecting and compiling that data, and a framework for using this data in analytical models (e.g. static MFA or dynamic MFA). The same is true to a lesser degree for the term IOA, which is sometimes used to describe all things associated with the development and analysis of both SUTs and IOTs. As pointed out in Section 4.1.1, existing terminology makes it difficult to distinguish these mostly independent steps within the analytical frameworks of MFA and IOA, making it difficult to single out one of them when discussing MFA or IOA.

>> *Conventional terminology is unable to fully describe shared system structure*

Another obstacle to clear and precise methodological comparison between MFA data, SUTs and IOTs is that conventional terminology fails to fully describe their shared system structure. The conceptual mapping of Section 5.2 shows that neither MFA terminology nor IOA terminology incorporate all conceptual distinctions identified in Section 5.1. Specifically, IOA terminology does not clearly distinguish system inflows and outflows from their origin and destination nodes. The same terms are used for both nodes and flows (see Section 5.3.1). Similarly, MFA terminology often neglects the origin and destination nodes of system inflows and outflows altogether (see Section 5.3.3). The same goes for the general SEM terminology proposed by Pauliuk et al. (2015) and Myers et al. (2018). Compared to these, the method-neutral conceptual framework presented in Section 5.1 provides clearer and more precise terminology for discussing the system structure of MFA data, SUTs and IOTs. Especially in comparative contexts where method-specific terminology is prone to invoke conceptual confusion.

>> *Unclear distinction between generic datatypes, and standardized implementations thereof*

Another point of ambiguity is that conventional terminology does not clearly distinguish between generic datatypes and standardized implementations thereof. The terms IOA, SUTs and IOTs are often used as direct synonyms for the standardized methods or data types prescribed by the SNA and SEEA. While strict adherence to these frameworks ensures a consistent use of terms and definitions within the field of IOA, it also obscures the difference between methodological conventions and fundamental characteristics of SUTs and IOTs. This thesis strongly argues for broadening this limited view on IOA, as Chapter 5 has repeatedly pointed out that deviating from the ‘conventional’ methodologies defined in Section 4.1 is not only possible, but may also provide analytical benefits and facilitate integration between methods.

The opposite is true for MFA, where a lack of strict terminological and methodological conventions leaves researchers with few precise and universally accepted terms and definitions (discussed Section 2.1 and 4.1). This reemphasizes the need for harmonization and standardization within MFA, something many have called for before (e.g. Brunner & Rechberger, 2017; Graedel, 2019; Pauliuk, 2020). Standardized frameworks such as EW-MFA and MSA do provide clear and unambiguous definitions that may act as a starting point for such harmonization. That said, the terminological mapping of Section 5.2 shows that these definitions are strongly linked to the specific MFA frameworks they were developed for, and an IOA-like coincidence between generic MFA and standardized implementations thereof should be avoided.

In the author’s view, conceptual clarity could be greatly improved by distinguishing generic methods or datatypes from standardized implementations thereof. For example by describing ‘EW-MFA data’ as a specific implementation of ‘generic MFA data’, ‘SEEA-based PSUTs’ as a specific implementation of ‘generic SUTs’ and ‘SNA-based MIOTs’ as specific implementations of ‘generic IOTs’. Using such terminology acknowledges the possibility to deviate from established standards, while not standing in the way of further methodological and terminological harmonization.

>> *The terms PSUT, PIOT and MFA data leave ambiguity about their unit-of-account*

While the terms PSUT and PIOT clearly distinguish them from the more conventional monetary IOA data, they do not very specifically describe the actual unit-of-account that is used. As illustrated in Section 5.4.1, both PSUTs and PIOTs may either record flows in units of mass (e.g. tonne), material-specific mass (e.g. kgCu, kgFe, tCO₂) or energy units (e.g. MJ). To eliminate this ambiguity, it would be wise to denote each of these subtypes using a unique term.

The same is true for MFA data, which may refer either to an account expressed in units of mass (e.g. tonne) or material-specific mass (e.g. kgCu, kgFe, tCO₂). In this case however, terminology already exists to distinguish the two: bulk-MFA data for accounts expressed in simple mass units and Substance Flow Analysis (SFA) data for those expressed in units of material-specific mass (see Section 5.4.1). Adopting these terms more broadly would improve clarity where context leaves it unclear what unit-of-account is used.

>> *Markets are modeled in SUTs and IOTs, but are not acknowledged*

MFA datasets often include explicit market processes. At first sight, SUTs and IOTs do not. However, the conceptual mapping and subsequent terminological comparison of Section 5.2 and Section 5.3 corroborate the observation by Pauliuk et al. (2015) that distributive markets are implicitly included in the rows of SUTs and IOTs. In both data types, each row corresponding to a residual or product essentially shows how these residuals and products are redistributed from the industries that supply them to the industries that use them. This includes the industry rows of IOTs, which due to the one-to-one correspondence between products and industries also represent distributive markets for the corresponding product output (see Section 5.4.2). To better understand this role of markets in IOA data, it would be helpful to explicitly refer to the rows of SUTs and IOTs as such (e.g. markets for products and markets for residuals instead of just products and residuals)

6.1.2 Terminological Alignment between Data Types

This section synthesizes the initial observations made in Section 5.3 on the terminological alignment between data types with the additional context provided by the closer conceptual comparison of Section 5.4. These synthesized findings directly contribute to answering Subquestion 2 in Section 6.2.

>> *Terminological alignment within, but not between MFA and IOA*

An important observation made from the conceptual mapping and subsequent assessment of terminological alignment presented in Section 5.2 and Section 5.3 is that terminology within the fields of MFA and IOA is largely harmonized across data types, but that there are clear terminological differences between the fields of MFA and IOA. The only true examples of aligned terminology are the terms imports and exports, which refer to trade flows in every data type. Besides these, significantly different terms are used to refer to similar underlying concepts. The most notable examples highlighted in Section 5.3.2 are: (i) processes in MFA <-> sectors or industries in IOA; (ii) stocks in MFA <-> capital in IOA; (iii) markets in MFA <-> rows for residuals and/or products in SUTs and IOTs.

As illustrated throughout the closer conceptual comparison of Section 5.4, the first two reflect the focus of MFA on material flows in general, compared to the focus of IOA on economic transactions. Because the system boundary of conventional SUTs and IOTs is limited to productive industries of the economy, transformative nodes necessarily represent these industries (see Section 5.4.1 and Section 5.4.2). For the same reason, the only stocks that are considered in conventional SUTs and IOTs are the productive capital stocks used in economic production (Section 5.4.4). By contrast, the lack of explicit terms for the residual and/or product markets in SUTs and IOTs seems to be unrelated to the economic focus of IOA data. In this case, IOA terminology simply reflects the tabular structure of SUTs and IOTs, while not reflecting the real-world activities underlying them.

Apart from the differences between MFA and IOA that are listed above, Section 5.3.2 also notes that IOA terminology is generally more conceptually specific than MFA terminology. In other words, IOA data terminology distinguishes between more conceptually distinct elements than MFA data. For example PSUTs and PIOTs use different terms to refer to different types of flows (i.e. products, residuals and natural inputs) which may be specified further depending on their destination and/or origin (e.g. imports of products, intermediate consumption of products, collection and treatment of residuals). This difference is directly related to the typical levels of conceptual disaggregation between MFA data and IOA data, described in Section 6.1.5

>> *No evidence of conflicting terminology between data types*

A comparison in Section 5.3.2 of terminology that is shared between MFA data, SUTs and IOTs finds that the interpretation of these shared terms largely aligns across data types, and does not depend on context. Even the closer conceptual comparison of Section 5.4 finds no conflicts between the method-specific definitions for identical or similar-sounding terms. So, while a lack of terminological alignment may hinder conceptual clarity, using conventional method-specific terminology is unlikely to lead to significant misinterpretations or confusion with other concepts when used outside its original methodological context.

6.1.3 Points of Conceptual Clarification to Support Findings

To allow for a clearer comparison between data types, conceptual clarification from a method-neutral perspective is provided throughout Chapter 5 of this thesis. Especially in Section 5.1 on our neutral conceptual framework, and in the closer conceptual comparison of Section 5.4. While the clarification given in these sections does not directly answer any of the research questions formulated in Chapter 3, it does help articulate the conceptual differences illustrated in Section 6.1.4 and Section 6.1.5. So for clarity, the conceptual clarification that is scattered throughout this thesis is condensed here into six key points.

>> *Data types can be described through nine fundamental conceptual building blocks*

The method-neutral conceptual framework developed in Section 5.1 describes the shared system structure of MFA data, SUTs and IOTs through nine fundamental conceptual building blocks: (i) intermediate nodes, (ii) intermediate flows, (iii) source nodes, (iv) system inflows, (v) sink nodes, (vi) system outflows, (vii) system boundary, (viii) resolution, (ix) balancing equations.

These nine elements are sufficient to fully describe MFA dataset, SUT or IOT, as illustrated by the fact the system structure of each could be fully mapped onto our method-neutral conceptual framework (see Section 5.2). Earlier method-neutral conceptual frameworks by Pauliuk et al. (2015) and Myers et al. (2018) contain similar elements. However, our framework adds an important distinction between intermediate nodes that are governed by balancing equations, and source and sink nodes outside the system boundary to which these balancing equations do not apply (see Section 5.4.1 and Section 5.4.2). Our framework also emphasizes the mostly understated importance of system boundary, resolution and balancing equations in the system structure of each method: without these elements an MFA dataset, SUT or IOT cannot be fully defined.

In practice, each of the fundamental building blocks may be used to represent a variety of different concepts, as illustrated in Section 5.1.2, Section 5.1.3 and the conceptual mapping of Section 5.2. However, from an abstract modeling perspective, these varying conceptual interpretations do not affect how these elements are modeled within the underlying directed graph structure.

>> *The structure of data types flexible and leaves room for flexible implementation*

To clearly define the objects of comparison for this thesis, multiple 'conventional' data types were defined in Section 4.1 using a single primary source for each. This eliminated any ambiguity related to poor terminological and methodological harmonization, and allowed the system structure of each data type to be clearly defined in Section 5.2. However, it was found that even these well-defined data types may be implemented in a wide variety of significantly different datasets.

To illustrate, Brunner & Rechberger (2017) only provide the basic building blocks for creating an MFA dataset (i.e. processes/nodes, flows, system boundary, resolution and balancing equations) but leave choices on system boundary, resolution and the specific interpretation of nodes and flows entirely up individual MFA practitioners. As shown throughout Section 5.4, the SNA and SEEA and EW-MFA manual all rigidly define a strict system boundary and clear balance requirements, while also prescribing standardized classification schemes for distinguishing process and flows. Nevertheless, even these standardized frameworks leave the level of disaggregation up to the practitioners that compile SUTs and IOTs (see Section 5.4.5). Of the analyzed data types, only MSA data is rigidly defined in all aspects by Bio by Deloitte (2015).

This lack of methodological rigidity makes general or abstract discussions about data types more difficult. However, unlike terminological ambiguity caused by a lack of harmonization (discussed in Section 6.1.1), it offers valuable flexibility to individual dataset compilers, who can adapt the data types to their specific needs and capabilities. As such, internal variety within methods must be taken into account in comparative studies like this thesis, by considering to what extent differences are bound to data type, or only to the specific datasets that are compared. This is especially relevant when the aim is to facilitate methodological integration. After all, ad-hoc choices made by individual practitioners are easier to challenge than well-established methodological standards and conventions.

>> *The choice of unit-of-account is a fundamental aspect of system definition*

Throughout Section 5.3 and Section 5.4, it becomes clear that the unit-of-account used to record flows has far-reaching consequences for the way different data types are interpreted. While this may seem like a trivial finding, it deserves emphasis due to its central but often understated importance.

Firstly, Section 5.4.1 reemphasizes that the unit-of-account determines what flows can and cannot be recorded in a certain data type. As described in Section 2.2, this has already received much attention in earlier literature in the sense that monetary accounts necessarily omit unpriced material flows such as emissions and wastes, while physical accounts fail to record massless flows such as service. Less often pronounced is the fact that material-specific accounts recorded in units such as kgCu or tCO₂ necessarily exclude flows that do not include the chosen reference material.

Secondly, Section 5.4.4 points to the unit-of-account as the main culprit for the different interpretation of stocks in MFA data and monetary IOA data: stocks expressed in physical units represent an actual accumulation of material (e.g. machines, building stocks, durable goods), whereas capital stocks expressed in monetary terms represent the value the same accumulated assets, which may fluctuate and depreciate even if the physical stock remains unchanged.

Lastly, Section 5.4.3 shows that the unit-of-account affects how balancing equations are interpreted: monetary accounts ensure consistency with the circular flow of income principle, while physical accounts ensure consistency with

the principles conservation of mass principle or conservation of energy. As indicated by Merciai & Heijungs (2014), De Koning et al. (2015) and Majeau-Bettez et al. (2016), consistency with one of these principles does not necessarily imply consistency with others. As a result, only multilayer accounts with balance across layers (e.g. multilayer HSUTs and multilayer HIOTs) can guarantee consistency with multiple balance principles at once.

>> *Satellite accounts may greatly expand scope for any dataset*

The system boundary (incl. unit-of-account) determines what flows can be described in a given set of MFA data, SUTs or IOTs. However, the closer conceptual comparison of Section 5.5 indicates on multiple occasions that additional information can be included with relative ease by extending the core dataset with independent satellite accounts, thereby expanding the scope beyond the system boundary of the core dataset. Examples are: the inclusion of unpriced residual flows such as wastes and emissions in monetary SUTs and IOTs (see Section 2.2.4 and Section 5.5.1); the inclusion of stock magnitude in both MFA data and IOA data (see Section 5.5.4); the inclusion of net stock changes in SUTs and IOTs, as well as stock inflows from and stock outflows to processes outside the production boundary of the SNA (Section 5.5.4).

As argued in Section 2.2.4, combining independent datasets like this is possible for any data type, at least in principle. Developing new ways of doing so still seems to mostly be an open methodological frontier. Over the years, researchers have repeatedly come up with new ways of combining and extending datasets for use in novel analytical models that yielded new and valuable insights. Examples of such methodological inventions are EEIOA (Leontief, 1970; Duchin, 1990), WIO (Nakamura & Kondo, 2002) and endogenous capital IOA (Lenzen & Treolar, 2004; Söldersten et al., 2018a, 2018b) and economically-extended MFA (Kytzia et al., 2004). In the view of the author, there is no reason to believe that such ingenuity has reached an end.

>> *Modeling multi-outflow nodes may require subjective allocation when analyzing data*

As argued in Section 5.4.2, the usability of MFA data, SUTs and/or IOTs largely depends on the degree to which relationships between flows can be established from the data recorded in them. What relationship is of interest depends on the type of analysis. For purposes such as footprint analysis and scenario analysis, the question is how the demand for a process's functional outputs drives waste generation and the demand for intermediate inputs. For purposes such as origins analysis and footprint analysis, the question is what inflows to a process physically end up in what outflows.

Section 5.4.2 also illustrates that these relationships between flows can only be unambiguously inferred for nodes that have a single flow to which all other flows must be necessarily attributed. In other words, footprint analysis and scenario analysis require monofunctionality (i.e. nodes with a single functional flow), while origins analysis and fate modeling require nodes to have either a single physical inflow, or a single physical outflow (i.e. nodes must be traceable). If these conditions are not met, subjective allocation is needed to establish a mathematical relationship between flows (e.g. through transfer coefficients in MFA, or allocation constructs in IOA). Both of these situations are more-or-less analogous to the allocation problem in LCA.

That said, if sufficiently detailed input data is available, the need for subjective allocation can largely be avoided by disaggregating processes into monofunctional or traceable sub-processes. This is discussed in greater detail within Section 5.4.2 based on an earlier study by Majeau-Bettez et al. (2016).

6.1.4 Irreconcilable Conceptual Differences between Data Types

Throughout Chapter 5, only two truly irreconcilable differences were found. These are recapped in this subsection and later combined with the convention-bound differences discussed in Section 6.1.5 to answer subquestion 3 and subquestion 4 in Section 6.2.

>> *Data types with varying units-of-account have fundamentally different interpretations*

As observed in Section 2.2, the unit-of-account is one of the main distinguishing features between the different data types analyzed within this thesis. Section 5.4.1 elaborates on this by finding that different data types either record flows in mass units or material-specific mass units (MFA data, PSUTs & PIOTs), monetary units (MSUTs & MIOTs), energy units (PSUTs & PIOTs), or a combination of these (HSUTs, HIOTs, multilayer HSUTs & multilayer HIOTs).

As emphasized in Section 6.1.2, these differences in unit-of-account have far-reaching effects on system boundaries, the interpretation of stocks, and the interpretation of balancing principles. Put shortly: datasets expressed in different units-of-account necessarily record different aspects of socio-economic metabolism, even when all other elements of the datasets align.

For this reason, direct unit conversions of full MFA and IOA datasets should generally be avoided, as should the use of analytical methods which rely on the validity of such unit conversions (e.g. EEIOA and WIO-MFA). Nevertheless, it cannot be denied that these approaches may still offer valuable insights if no better alternative is available, as long as a critical attitude is maintained and all limitations are properly considered.

>> *IOTs uniquely require a one-to-one correspondence between industries and products*

Because the primary application of IOTs is to analyze the interdependence between economic sectors, each intermediate node modeled in an IOT must be monofunctional (Section 5.4.2 and Section 6.1.3). In practice this means that IOTs, unlike MFA data and SUTs, assume a one-to-one correspondence between products and industries. While this assumption is useful from a modeling perspective, it often misrepresents reality. Many real-world economic activities simultaneously produce multiple (by)products. Such instances of coproduction or joint production cannot be captured within the structure of IOTs, making IOTs less suitable for descriptive accounting than SUTs and MFA data.

This difference is less relevant for MIOTs, whose construction typically involves the construction of a more detailed MSUT as an intermediate step. Together, the MSUT and corresponding MIOT provide the best of both worlds: the descriptive power of SUTs and the analytical usefulness of IOTs. However, the descriptive limitations of IOTs become relevant when PIOTs are directly constructed from MIOTs (e.g. using WIO-MFA). In these cases no complementary PSUT is available.

6.1.5 Convention-bound differences between data types

All conceptual distinctions not discussed in Section 6.1.4 may be condensed into five key differences relating to misaligned system boundaries and/or disaggregation schemes. All are convention-bound, and seem to be resolvable through terminological harmonization, alignment of disaggregation schemes and system boundaries, or by using satellite accounts to align scope where system boundaries do not align. Together with Section 6.1.4, the discussion provided here informs the answers to subquestions 3 and 4 in Section 6.2.

>> *Level of standardization and harmonization varies greatly between data types*

As discussed throughout this thesis (especially in Chapter 2, Section 4.1.2, and Section 6.1.1), a significant difference between data types lies in the level of terminological and methodological standardization. Harmonization between data types should, at least in principle, be able to eliminate these differences.

To again give a short overview of the level of standardization for different data types: almost all MSUTs and MIOTs are highly standardized through the SNA (United Nations, 2025) and the handbook of SUTs and IOTs (United Nations, 2018). Most large-scale PSUTs and PIOTs also adhere to these guidelines, as well as to the SEEA (United Nations, 2014). MSA data and EW-MFA data are also highly standardized through their corresponding methodological frameworks, with the latter also being closely aligned with the SEEA (Bio by Deloitte, 2015; Matos de Torres, 2020; UNEP, 2023).

By contrast, the vast majority of MFA data falls under the category of generic MFA data, for which there are no universally-accepted methodological and/or terminological frameworks. HSUTs and HIOTs (single-layer and multilayer) are currently still too novel to be included in any standard framework. However, as these data types build on conventional monetary and physical IOA data it can be expected that they will be incorporated within the SNA and/or SEEA at some point in future.

>> Economic boundaries are not fully aligned between standardized data types

Apart from the fundamental differences that result from varying units-of-account indicated in Section 6.1.4, the closer conceptual comparison of system boundaries (Section 5.4.1) found one other difference between MFA data, SUTs and IOTs: all analyzed data types except generic MFA use economic boundaries to define their system boundary. However, the exact definitions of these economic boundaries vary between data types. As described in Section 5.4.1, SUTs and IOTs focus on the productive economy as defined in the SNA and SEEA. Unlike MSA data and EW-MFA data which cover the full economy, this excludes in-use stocks and final consumption by households (see also Section 6.1.3). The definition of the full economy also varies between EW-MFA data and MSA data, as the first more-or-less adopts the SNA definition of the full economy, while MSA data uses its own ad-hoc definition. In principle, all of these differences should be reconcilable by harmonizing system boundary definitions across data types, or developing unambiguous correspondence tables to show how the system boundaries of different standardized data types relate.

>> Conventional unextended IOA data gives an incomplete account of stocks

While there is a significant difference between the interpretation of stocks in MFA data and in traditional monetary IOA data, this is shown to result mostly from their different units-of-account (discussed in Section 6.1.2). All data types that record flows in mass units describe stocks in terms of physical material accumulation. Nevertheless, even physical IOA data often omits key information on stocks. However, all this information can in principle be included by using a satellite account, or by disaggregating final consumption.

The first difference is the way stock magnitude is recorded (see Section 5.4.4 and Section 6.1.2). While MFA data does not require stock magnitude to be included, when it is included, it is generally recorded alongside net stock change. By contrast, SUTs and IOTs have no designated space to record stock magnitude. The asset account of the SNA and SEEA does however record stock magnitude. Hence, stock magnitude can be communicated in IOA data by presenting the asset account alongside it as a satellite account.

The second difference is that due to their system boundary (Section 5.4.1), SUTs and IOTs typically only record stock inflows from, and stock outflows to, the productive economy as defined by the production boundary of the SNA. As described in Section 5.4.4, this may lead to the exclusion of some stock inflows and outflows. This in turn makes it problematic to infer net stock changes directly from an SUT or IOT. However, the asset account of the SNA and SEEA again presents a solution, as this allows stock inflows and outflows unrelated to the productive economy to be recorded.

The third and last difference is that SUTs and IOTs often limit their coverage of stocks to Gross Capital Formation (i.e. durable assets accumulated by productive industries), while not recording the accumulation of durable goods by final consumers. This is because many SUTs and IOTs fail to distinguish between the consumption of durable goods and non-durable goods in their final consumption columns. However, as discussed in Section 5.4.4 this is purely a matter of disaggregation. As described in United Nations (2018), the standard classification scheme within the SNA for household final consumption (COICOP) does allow consumption to be broken down into the consumption of services, non-durables, semi-durables and durables. This means that the omission of in-use stocks held by final consumers is related to the resolution of available data, and is not inherent to SUTs and IOTs as a data type.

>> Typical disaggregation patterns vary between data types

The exact resolution of a datasets is highly situational and dependent on the preferences, needs and capabilities of its compiler, as discussed in Section 5.4.5 and Section 6.1.1. Nevertheless, in Section 5.4.5, significant differences were found between data types in the way that the system of interest is typically disaggregated. While purely convention-bound, these differences have a notable effect on the amount of information that is typically captured by different data types. It also affects comparability between datasets of different data types.

Firstly, the terminological comparison of Section 5.3 showed that IOA data is generally more conceptually specific than MFA data when distinguishing conceptually distinct nodes and flows. In other words, IOA data is generally more conceptually disaggregated. One example of this is that IOA data distinguishes between product flows, residual flows and natural input flows, whereas most MFA data does not. Another example is that SUTs and IOTs, unlike MFA data, break down system outflows into exports, final consumption, and gross capital formation, each of which may respectively

be disaggregated further by region, institutional sector (i.e. Households, Government, NPISH) or asset class.

Secondly, and more importantly, Section 5.4.5 observes that where MFA data and IOA data are disaggregated along the same axes, this is often done using (partially) incompatible classification schemes: both the MSA and EW-MFA frameworks prescribe unique classification schemes which are not compatible (in the case of MSA) or not fully compatible (in the case of EW-MFA) with those prescribed by the SNA and SEEA. In turn, the ad-hoc resolution choices made by compilers of generic MFA data rarely align with any of these standardized classification schemes.

Such incompatible disaggregation greatly reduces the ability to compare datasets of different data types, as information can only be compared for nodes and flows that are defined in the same way (see Section 5.4.5 and Section 6.1.1). Admittedly, even datasets which are disaggregated differently may still be comparable to the extent that differences in resolution between datasets can be aggregated out. However, investigating the extent to which this is typically possible is beyond the scope of this thesis.

>> *MFA data, SUTs and IOTs implement distributive markets differently, influencing traceability*

Markets are included in every analyzed data type. As discussed in Section 6.1.1 these are explicit in MFA data, and implicitly modeled in the rows of SUTs and IOTs. However, apart from these terminological differences, the exact conceptual implementation varies between data types, as found by conceptual comparison of Section 5.4.2.

In any IOT, which assumes a one-to-one correspondence between products and industries, each row corresponding to an industry can essentially be interpreted as a combination of that industry with an implicit distributive market for its primary product output. As this market necessarily has only one inflow, all of its outflows are traceable back to the industry that produced the corresponding product. As discussed in Section 6.1.3 on multi-outflow nodes and the problem allocation, this provides various modeling benefits.

By contrast, the markets represented by the rows in SUTs are not necessarily traceable, as each of the corresponding products and residuals are typically produced by multiple sectors, but also used by multiple sectors. The same goes for the rows corresponding to the generation and use of residuals in PIOTs. However, as shown in an earlier study by Majeau-Bettez et al. (2016) and elaborated on in Section 5.4.2, such markets can easily be made traceable by disaggregating them until each row of the SUT or IOT corresponds to a product or residual that is uniquely produced or consumed by a single industry.

While the markets that are included in generic MFA data are often traceable, this is mostly related to the high level of sectoral aggregation of most generic MFA datasets. As the resolution of MFA dataset increases, markets quickly start to face the same issues as conventional SUTs, as illustrated by the lack of traceable markets in MSA data. Like is the case with SUTs however, any MFA dataset can in principle be made traceable by sufficiently disaggregating the modeled markets until each corresponds to a unique producing or consuming sector.

6.2 Answers to Research Questions

In this section the synthesized findings of Section 6.1 are discussed in light of the research questions posed in Chapter 3, addressing them one-by-one. After first giving a short answer to each question, a more elaborate answer is given to provide additional context.

Subquestion 1:

What factors undermine the clarity and precision of methodological discussion on MFA data, SUTs and IOTs?

Short answer: As encountered throughout the writing of this thesis, a lack of terminological harmonization and conceptual ambiguity surrounding the definitions of MFA data, SUTs and IOTs greatly undermines the clarity and precision of methodological discourse on these data types. While context may often be enough to overcome such ambiguity, this context is quickly lost when discussing multiple data types simultaneously in a comparative context.

Elaborate answer:

Unlike the answer to other research questions, this answer does not follow directly from the results presented in Chapter 5. Rather, the answer largely lies in the preliminary work described in Section 4.1, which was needed to enable a clear and precise comparison of MFA data, SUTs and IOTs in the first place. As summarized in Section 6.1.1, four points of conceptual ambiguity had to be addressed in writing this thesis:

1. The broad interpretation of MFA and IOA makes it difficult to isolate MFA data, SUTs and IOTs
2. The distinction between generic and standardized data types is often not clearly articulated
3. Conventional terminology inadequate describes for shared system structure
4. Markets are implicitly modeled in SUTs and IOTs but rarely acknowledged
5. The terms PSUTs, PIOTs and MFA data are ambiguous about their unit-of-account

These ambiguities may not be problematic when discussing a single data type, as context usually provides sufficient clarity. However, they seriously increase the risk of conceptual confusion when discussing multiple data types simultaneously in a comparative context, as repeatedly found when writing this thesis.

Subquestion 2:

To what extent do MFA data, SUTs and IOTs use similar terminology to describe their underlying directed graph structure?

Short answer: This thesis finds clear terminological differences between the fields of MFA and IOA that reflect their respective focuses on recording the economic transactions and recording material flows in general. That said, no examples are found of shared terms with conflicting definitions. When not comparing terminology not between but within the fields of MFA and IOA no major terminological differences are found at all.

Elaborate answer:

The answer to this question follows directly from key findings presented in Section 6.1.2, which in turn synthesizes observations made during the conceptual mapping of Section 5.2 and subsequent assessment of terminological and conceptual alignment presented in Section 5.3. While the successful application of the conceptual mapping approach reemphasizes claims by Pauliuk et al. (2015) and Myers et al. (2018) that MFA data, SUTs and IOTs largely describe the same structural and conceptual elements, it was found that MFA and IOA use significantly different terminology to distinguish these concepts. However, there seem to be no significant terminological differences between different subtypes of MFA data, or between SUTs and IOTs.

Importantly, there also seem to be no direct terminological conflicts where similar-sounding terms have significantly different interpretations depending on the context. So, while the terminological differences between MFA and IOA may hinder comparative discussion between data types, they are not expected to lead to significant misinterpretations.

Subquestion 3:

To what extent do the observed terminological similarities and differences between MFA data, SUTs and IOTs relate to underlying conceptual distinctions?

Short answer: Some terminological differences between data types, including the distinct names of each data type are found to reflect conceptual differences. However, it also seems that many terminological differences obscure underlying conceptual similarities, especially between MFA data, PSUTs and PIOTs which are all expressed in the same unit-of-account and largely describe the same concepts.

Elaborate answer:

After a closer investigation in Section 5.4 of the comparable method-specific concepts identified in Section 5.3, a number of key conceptual distinctions were found, as summarized in Section 6.1.4 and Section 6.1.5:

1. Data types with varying units-of-account have fundamentally different interpretations
2. IOTs uniquely require a one-to-one correspondence between industries and products
3. Level of standardization and harmonization varies greatly between data types
4. Economic boundaries are not fully aligned between standardized data types
5. Conventional unextended IOA data gives an incomplete account of stocks
6. Typical disaggregation patterns vary between data types
7. MFA data, SUTs and IOTs typically implement distributive markets differently, influencing traceability

This thesis finds that difference #1 and #3 are not well-reflected by terminological distinctions. In both cases, this relates to ambiguous naming conventions indicated in Section 6.1.1. Firstly, naming conventions of data types do not reflect the fact that physical accounts such as MFA data, PSUTs and PIOTs may be expressed in mass units, material-specific mass units, or energy units. Secondly, the difference between generic data types and standardized implementations thereof is often not specified, especially when discussing SUTs and IOTs. Apart from these exceptions however, all conceptual distinctions are well-reflected by the naming conventions of data types and terminology used to describe them.

However, while conceptual differences are well-reflected in terminological differences, conceptual similarities are not. Apart from the nuanced conceptual differences noted above, the results presented throughout Chapter 5 primarily show similarities between the underlying concepts that are described by MFA data, SUTs and IOTs. Especially between MFA data, PSUTs and PIOTs, which are all expressed in the same unit-of-account. This does not correspond to the answer of Subquestion 2 that notes almost no terminological alignment between MFA and IOA.

Subquestion 4:

To what extent can the revealed terminological and conceptual distinctions between MFA data, SUTs and IOTs be overcome by adapting or revising established terminological and methodological conventions?

Short answer: Of the conceptual and terminological differences identified within this thesis, most seem reconcilable by harmonizing terminology, disaggregation schemes and system boundaries, or by extending conventional datasets using satellite data. Only two fundamental, irreconcilable differences were found: First, data types expressed in different units-of-account describe substantially different aspects of both material flows and stocks. Second, the descriptive potential of IOTs is limited compared to MFA data and SUTs, as they require a one-to-one correspondence between products and sectors.

Elaborate answer:

The best way to answer this subquestion is to go through the conceptual differences listed in the answer to subquestion 4 one-by-one, stating if and how they could potentially be resolved:

1. Differences in unit-of-account are key distinguishing characteristics separating different data types, especially for SUTs and IOTs (see Chapter 2). As such, it is safe to say that these differences are irreconcilable.
2. Similarly, the one-to-one correspondence between products and industries that is required in IOTs is one of the key distinctions that separates IOTs from SUTs.
3. Differences in the level of standardization and harmonization can clearly be overcome, in particular through standardization efforts within the field of MFA.
4. Differences in the way economic boundaries are defined could be overcome by harmonizing these definitions.
5. A more complete account of stocks could be given in SUTs and IOTs in three ways: (i) separating the final consumption of durable and non-durable goods, to track the accumulation of in-use stocks held by final consumers;

- (ii) extending conventional SUTs and IOTs with an asset account to record stock inflows and outflows unrelated to the productive economy; (iii) extending the system boundary beyond the productive economy, like is done in most MFA data.
6. Differences in disaggregation patterns could be overcome by aligning the classification schemes used in MFA with those prescribed by the SNA and SEEA.
 7. Differences in the way distributive markets are included can be overcome by explicitly including markets in every dataset and using aligned the same disaggregation schemes.

Apart from these conceptual differences, there are also the terminological differences between MFA and IOA that were pointed out in the answer to subquestion 2. Needless to say that these are, at least in principle, surmountable through terminological harmonization. This makes that the only irreconcilable differences are conceptual difference #1 and #2, which are so closely linked to the distinguishing characteristics of the analyzed data types that they can be considered fundamental differences.

Main Research Question:

How do terminological and conceptual differences between Material Flow Analysis (MFA) data, Supply-Use Tables (SUTs) and Input-Output Tables (IOTs) affect the potential for integration between these data types?

Short answer: Irreconcilable conceptual differences prevent the full unification or direct unit conversion of data types expressed in different units-of-account (e.g. monetary and physical units), as well as the unification of IOTs with MFA data or SUTs. However, the results of this thesis suggest that other forms of integration are mainly held back by convention-bound differences that, with sufficient effort, could in principle be resolved. Examples include the potential unification of MFA data and PSUTs, or the combined use of monetary and physical data in multilayer HSUTs and HIOTs.

Elaborate answer:

Based on the synthesized findings of Section 6.1 and the answers to the subquestions given in Section 6.2, it may be concluded that terminological and conceptual differences between data types, especially between MFA data and IOA data, certainly pose obstacles to methodological integration. With sufficient will from both MFA practitioners and IOA practitioners however, it seems that most differences between data types could be overcome by revising established conventions.

What follows from the answer to subquestion 4, is that the only two types of methodological integration that are outright prevented by irreconcilable conceptual differences are the unification of data types expressed in different units-of-account (e.g. monetary data and physical data), and the unification of IOTs with MFA data and SUTs. This supports the careful suggestions by Pauliuk et al. (2015) and Myers et al. (2018) that unification between MFA data and PSUTs is possible, at least in principle. It should also be noted that the two irreconcilable differences between data types only prevent outright unification. They have no significant implication for other proposed types of integration, such as the combination of monetary and physical data in multilayer HSUTs and HIOTs (Mercai & Schmidt, 2028; Mercai, 2019). The answers to subquestions 2, 3 and 4 suggest that such integration between different subtypes of IOA data seems largely unobstructed by terminological and conceptual differences. By contrast, between MFA data and IOA data there remain various convention-bound differences that stand in the way of immediate integration. As a result, a revision of well-established conventions would be necessary to enable any substantial integration between the fields of MFA and IOA. Most importantly, terminology would need to be harmonized and system boundaries and classification schemes aligned. While possible in principle, this would require many individual practitioners to change their ways without gaining any direct benefit from this change.

6.3 Implications

6.3.1 Strategies to Increase Conceptual Clarity Within MFA and IOA

The points of terminological ambiguity presented in Section 6.1.1 all present opportunities to increase conceptual clarity within MFA and IOA. This section discusses how reevaluating the terminology by which MFA data, SUTs and IOTs are described can facilitate more precise discourse on these methods, hopefully facilitating methodological development.

>> *Articulate and emphasize independence of different analysis steps in MFA and IOA*

As discussed in Section 6.1.1, conventional MFA and IOA terminology often fails to make a clear distinction between independent analysis steps such as raw data collection, data storage (e.g. in MFA data, SUTs or IOTs) and data analysis (e.g. leontief IOA model, static MFA or dynamic MFA). This makes it difficult to isolate one of these steps when speaking of these methods, and hinders methodological integration by obscuring which analysis steps in MFA and IOA fulfill similar functions.

To improve conceptual clarity, it would be helpful to articulate and emphasize the independence of individual analysis steps. For example by developing an overarching analysis framework for MFA and IOA that breaks down the methodologies into independent steps from raw data collection to analysis and interpretation, similar to the way the LCA methodology is broken down into different phases (ISO14040). Alternatively, data pipeline designs developed in the field of data science could also offer valuable baselines for clarifying the analysis steps of MFA and IOA. Figure XXX provides an example of this.

>> *Ensure naming of data types convey key distinctions between them*

This thesis has shown that some key differences between data types are not conveyed by the conventional way of naming them, as pointed out in Section 6.1.1. Reevaluating the naming of data types to reflect these differences would increase awareness of said differences and improve conceptual clarity. As a starting point for this, alternative naming conventions are proposed in **Figure 6.1**.

A first recommendation is to clearly distinguish between generic methods and standardized implementations thereof. Secondly, the distinction between material-specific and non-material-specific MFA data, PSUTs and PIOTs could be articulated more clearly. Lastly, the author suggests inventing a new term for PSUTs and PIOTs expressed in energy units to differentiate them from those expressed in mass units.

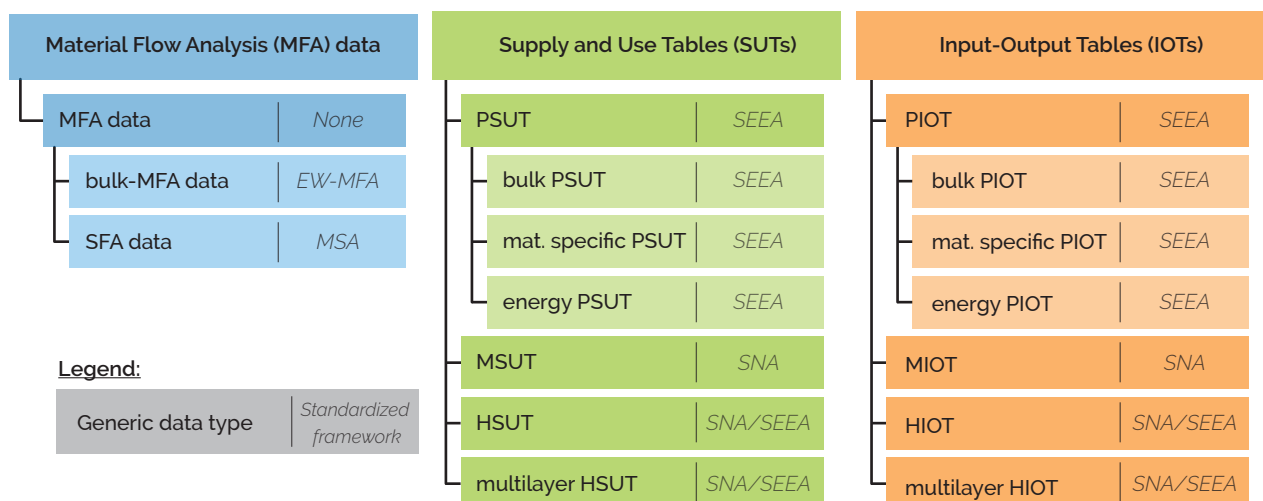


Figure 6.1: Proposed naming conventions that more clearly reflect key distinctions between data types.

Note. This naming structure distinguishes generic data types from standardized implementations thereof, while also referring to physical accounts based on their unit-of-account (i.e. energy units, material specific mass, or bulk-mass)

>> *More clearly articulate the underlying directed graph structure*

This thesis has shown that all subtypes of MFA data, SUTs and IOTs can be interpreted as expressions of an underlying directed graph structure, described by nine distinct fundamental building blocks (see Section 6.1.2). However, it also shows that conventional terminology does not always reflect these distinctions (see Section 6.1.1). What is particularly difficult to describe in MFA and IOA is the distinction between nodes and flows, and the distinction between source nodes, sink nodes and intermediate nodes (see Section 6.1.1). This limits precision when describing the shared system structure of MFA data, SUTs and IOTs, and should be addressed to improve conceptual clarity and facilitate comparisons between these methods.

The neutral conceptual framework developed in this thesis (Section 5.1) offers a clear baseline for distinguishing between structurally distinct elements, based on graph theory terminology. However, instead of adopting this framework directly, it is likely more fruitful to build on existing MFA and IOA terminology by clarifying method-specific terms and introducing new terms only where necessary.

>> *Work towards terminological harmonization within and between methods*

Whereas the previous points in this subsection discuss how purposeful introduction of new terms can improve conceptual clarity within MFA and IOA, this thesis has also shown that unnecessary terminological variety reduces conceptual clarity. As discussed in Section 4.1 and elaborated in Section 6.4, a significant obstacle in writing this thesis was that not all concepts have a single universal definition: different authors may use different vocabularies, making it difficult to identify precisely what concepts individual authors are referring to when using a term. Especially generic non-standardized MFA data deals with this issue, as noted before by other authors (e.g. Pauliuk, 2020; Brunner & Rechberger, 2017). In these cases, terminological harmonization and standardization within methods would greatly improve conceptual clarity.

That said, it is not only terminological variety within methods that reduces conceptual clarity, but also terminological variety between methods. As shown by the conceptual mapping of Section 5.2 and further discussed in Section 6.1.4, many conceptual similarities between data types are obscured by the fact that significantly different terms are used to describe structurally and conceptually similar elements of MFA data, SUTs and IOTs. In the long term, this could be resolved through terminological harmonization between methods. However, because this would necessarily involve a significant overhaul of existing terminological conventions in either MFA or IOA, this would likely face resistance by practitioners. Considering this, the author suggests that in the short term, it is more practical to focus on refining existing terminology for each method individually, as outlined earlier throughout this subsection.

6.3.2 Pathways Towards Further Integration Between MFA and IOA Data

>> *Further develop neutral terminology to precisely discuss shared system structure*

As discussed in the last point of Section 6.3.1, the conventional terminology used to describe different data types obscures structural and conceptual similarities between them, making precise discourse on the shared elements of these data types difficult. While terminological harmonization between methods may solve this issue in the long term, this does not help those working on the methodological integration between MFA and IOA in the short term. To address this problem, the author suggests that a separate method-transcendent conceptual framework is developed to use in parallel to existing method-specific terminologies. The neutral conceptual framework developed in Section 5.1 of this thesis provides a good baseline for this, although the robustness of definitions could be improved and the level of conceptual detail increased.

>> *Standardize and harmonize system boundaries and disaggregation schemes*

As pointed out in Section 6.1.2, equivalent node and flow definitions are a prerequisite for comparability between datasets. This limits the comparability of MFA datasets, as most generic MFA data uses ad-hoc system boundaries and process definitions that vary significantly between studies. Avoiding such unnecessary inconsistencies is a central objective underlying standardized frameworks such as EW-MFA (UNEP, 2023) and MSA (Bio by Deloitte, 2015;

Matos de Torres, 2020), as well as the SNA and SEEA (United Nations, 2014, 2025). However, as discussed in Section 6.1.4, the current situation is that each of these standardized frameworks define different economic boundaries to demarcate the system of interest, and use incompatible classification schemes to disaggregate this system of interest.

A possible solution to this is to harmonize standardized system boundaries and classification schemes across MFA and IOA. In the view of the author, the most likely direction for such harmonization is for both MFA to adopt and build on classification schemes prescribed by the SNA and SEEA (United Nations, 2014, 2025). After all, these are already well-established, and generally more detailed than those of EW-MFA and MSA (see Section 6.1.4). To make these classification schemes applicable at the typical resolution of generic MFA data, extending with further levels of disaggregation may be necessary. This should be a joint effort between MFA practitioners, IOA practitioners, and statistical institutions, who all stand to benefit from such standardization.

>> Consider using MFA data, PSUTs and PIOTs side-by-side for cross-validation and balancing

This thesis has shown that if disaggregation schemes align, MFA data and PSUTs (and to a lesser degree PIOTs) largely record the same type of information, as indicated throughout Section 6.1 and Section 6.2. As a result there may be opportunities to cross-compare these datasets to assess the extent to which material flow data that is collected and processed using MFA methods aligns with data that is collected and processed using IOA methods. Beyond simply enabling cross-validation, this compatibility between MFA data, PSUTs and PIOTs could further improve robustness of both MFA data and IOA data by introducing new opportunities for balancing.

>> Consider adopting a PSUT structure as the unified standard for recording material flow data

As pointed out in Chapter 2, there have been multiple calls over the years for a single standard for recording information on material flows (e.g. Pauliuk et al., 2015, 2019; Myers et al, 2018, 2019; Pauliuk, 2020). This thesis reemphasizes that MSUTs and MIOTs are not appropriate for this purpose. Even if converted to physical units using methods such as WIO-MFA (Nakamura, 2007), they record substantially different aspects of material flows and stocks than physical accounts do (see Section 6.1.4). The same goes for PIOTs, which have inherently limited descriptive potential because they require a one-to-one correspondence between products and sectors. This leaves MFA data and PSUTs as the most suitable candidates to form the basis of a unified data type for recording material flows. This thesis proposes to opt for the latter for three reasons:

- (i) Like MFA data, the PSUT structure is significantly versatile, especially when looking beyond the standardized implementations of the SNA and SEEA: system boundary and resolution is flexible, they can be material-specific or not, traceability can be ensured if sufficiently disaggregated and stocks can be included by adapting the system boundary or including a separate asset account.
- (ii) Well-proven methods exist to convert PSUTs to PIOTs. This opens the way to use the PSUTs in a wide variety of analytical approaches which depend on a one-to-one correspondence between products and industries. Examples include Leontief-based footprint analysis/consumption-based accounting and scenario analysis (e.g. Aguilar- Hernandez et al., 2018), CGE/IAM modeling and other econometric models (Lefebvre, 2023).
- (iii) Unlike MFA data, the standardization of PSUT is already largely underway, with the SEEA (United Nations, 2014) providing an authoritative and well-defined framework of best-practices, definitions and classification schemes which are aligned with other institutional accounting frameworks such as EW-MFA (UNEP, 2025) and the SNA (United Nations, 2025). The already large degree of alignment between the SEEA and SNA also facilitates the integration of PSUTs and MSUTs to create (multi-layer) HSUTs, which promise to provide more informative and robust insights than physical accounts or monetary accounts alone (Merciai & Schmitt, 2012; Merciai, 2019; Hoekstra, 2010).

In summary, PSUTs are just as useful as MFA data as a standalone physical account, but they can also easily be converted into other data types. This makes them useful for a wide variety of analytical purposes and -in the view of the author- a good candidate for becoming the standard structure for storing data on economic material flows.

>> *Consider using MFA data and PSUTs interchangeably for modeling applications*

Because the different data types can be converted into each other with relative ease due to their shared directed graph structure, there may be opportunities to use data types outside their original modeling discipline. For example, using SUTs and IOTs in MFA-like scenario studies based on Transfer-Coefficient (TC) and demand- or supply-driven fixed flows. Or using SUTs and IOTs in flow or supply-driven dynamic (MFA) models based on lifetime expectations. Investigating the actual prospects of this is outside the scope of this thesis.

6.4 Reflection on Methods

In this Section: the methods used throughout this thesis are reflected on. First Section 6.4.1 highlights general limitations of the approach taken to compare data types. These relate mostly to minor simplifications and shortcuts made to manage scope. Section 6.4.2 then reflects on the method-neutral conceptual framework, commenting on the initial motivation for its development as well as its proven effectiveness. The same is done in Section 6.4.3 for the conceptual mapping approach.

6.4.1 General Research Limitations

>> *Artificial definition of conventional data types*

A major obstacle to comparing MFA data, SUTs and IOTs is that no unequivocal definitions exist for any of these methods. Too much variety in the typical application of a single method quickly leads to terminological, conceptual and methodological ambiguity. The object analysis becomes hard to define.

To limit this ambiguity, this thesis uses a single primary literature source for each method to define a ‘conventional’ methodology and terminology of that method (Section 4.1). However, this approach is somewhat artificial and overlooks the fact that not all implementations of the analyzed data types are consistent with these ‘conventional’ definitions. This is especially true for generic MFA data, for which a lack of standardization gives researchers great freedom to choose their preferred methodology and terminology (see Section 6.1.2). As a result, some nuances and complexities are necessarily lost.

Seeing this limitation, results of this thesis that are closely related to our definition of ‘conventional’ methodologies should not uncritically be generalized to all MFA data, SUTs and IOTs. This mainly includes the conceptual mapping and terminological comparison presented in Section 5.2 and Section 5.3. That said, it is not expected to significantly affect the findings and recommendations presented here in Chapter 6.

>> *Terminological variety within methods not acknowledged*

As discussed in Section 6.1.1, one of the greatest challenges in writing about MFA data, SUTs and IOTs proved to be terminological ambiguity (i.e. one term referring to multiple concepts). Another challenge however was dealing with terminological variety within methods. Especially in colloquial language, multiple synonyms or near-synonyms may be used to refer to a single concept. To keep a clear and consistent vocabulary throughout this thesis, the choice was made to mostly ignore this terminological variety. In practice, the biggest implication of this choice is that terminological variety within methods is not acknowledged in the conceptual mapping and terminological comparison of Section 5.2 and Section 5.3. Otherwise, it should have no effects on the findings of this thesis.

>> *Comparison of Terms and Definitions is non-exhaustive*

This thesis has compiled an extensive and hopefully enlightening overview of the differences between different data types used to record information on material flows within the economy. However, it should be emphasized that the critical review of terms and definition that underlies this comparative overview was not exhaustive. While the author has fully read the most relevant chapters of the primary literature presented in Section 4.1, some parts of these sources remain unread. As a result, minor but consequential nuances may be overlooked in the writing of this thesis. As such, it would be prudent to involve MFA and IOA experts when refining or putting into practice the findings and recommendations of this thesis.

>> *Life Cycle Inventory (LCI) data excluded from comparison to reduce scope*

As discussed in Section 2.3 and 2.4, the research of Pauliuk et al. (2015) and Myers et al. (2018) play a large role in motivating the topic of this thesis. Both papers conclude that MFA data, SUTs, IOTs and Life Cycle Inventory (LCI) data share a similar underlying system structure, but fail to sufficiently address seemingly important terminological and conceptual differences in their comparison of these data types. This thesis aimed to further articulate and clarify these differences, focusing on MFA data and IOA data. A comparison with LCI data was excluded to reduce scope. However, extending the comparison of this thesis with LCI data would provide even greater insight into the prospects for integration between different types of Industrial Ecology data.

6.4.2 Reflection on Method-Neutral Conceptual Framework

As pointed out in Section 4.1.3 and in Section 6.1.1, using conventional method-specific terminology in comparative contexts makes it very difficult to have clear and precise methodological discussions. Switching back and forth between different method-specific terminologies when discussing multiple data types simultaneously quickly leads to confusion. This issue unquestionably needs to be addressed to improve the conceptual clarity and precision of any comparative study between these methods. The solution opted for in this thesis was to develop a method-neutral, graph-based conceptual framework to use as an alternative to method-specific terminology. However, alternative solutions could be argued for.

>> *The choice to deviate from conventional terminology with a method-neutral framework*

The argument to define an alternative conceptual framework to circumvent conventional terminology, is that its clarity is largely independent of the reader's own background. Within the isolated context of a single study, the method-neutral terminology has shown to be useful tool for comparative discussion, that remains understandable even if no other MFA and IOA practitioner adopts the same terminology in their day-to-day vocabulary. This could explain why earlier comparative studies of MFA and IOA (e.g. Pauliuk et al., 2015; Myers et al., 2018) take a similar approach: they present new concepts and definitions to clarify their ideas, without directly asking others to adopt the same terminology.

In the long term, an alternative solution could be to eliminate terminological differences between MFA and IOA by striving towards full terminological alignment. However, this would require many individuals to deviate from their usual vocabulary for little personal gain. Realistically, the majority of MFA and IOA practitioners rarely engage in the type of comparative methodological discussions that necessitate a common terminology. Developing an alternative method-neutral conceptual framework to exist alongside the conventional terminologies of MFA and IOA as an analytical tool remains the most elegant solution to improve the conceptual clarity and precision of methodological discussions.

>> *The choice to use directed graphs as basis for method-neutral conceptual framework*

The method-neutral conceptual framework developed in this thesis, as well as those by Pauliuk et al. (2015) and Myers et al. (2018), takes the concept of directed graphs or networks as the starting point for defining the shared structure of MFA data, SUTs and IOTs. Other approaches are certainly possible. For example, one could begin from the tabular structure of SUTs or IOTs and attempt to define the structure of all data types in terms of rows and columns. Conversely, one could attempt to translate SUTs and IOTs into MFA-like Sankey diagrams consisting of processes, flows and stocks. There is no reason why such approaches couldn't also be helpful in comparative discussions. In principle, any set mutually exclusive and collectively exhaustive terms that captures the shared structure of MFA data, SUTs and IOTs could serve this purpose. Nevertheless, there are various reasons to prefer a directed graph structure over the alternatives:

- (i) The graph-based approach builds on earlier efforts to compare and integrate data types within the field of IE, making it a natural extension of existing work.
- (ii) To those familiar with the concept of directed graphs, this approach clearly communicates the mathematical underpinnings of MFA data, SUTs and IOTs.
- (iii) Recognizing that visual network diagrams and adjacency tables are both common expressions of directed graphs intuitively reflects a crucial relationship between MFA diagrams, SUTs and IOTs. Namely, that all three are representations of a similar same real-life phenomenon: a network in which materials physically move (i.e. flow) from one place (i.e. node) to another.

6.4.3 Reflection on Conceptual Mapping Approach

One of this thesis' contributions is the conceptual mapping approach developed in **Section 4.2** and applied in **Section 5.2** and **Section 5.3**. Due to the generality of the approach, its applicability extends far beyond the context of this thesis. In principle, it should support any comparison of terminology and conceptual definitions across different conceptual frameworks. Nevertheless, the author is not aware of other studies, within Industrial Ecology or otherwise, that use a similar method for structuring a conceptual comparison. As such, this method deserves to be reflected on.

>> *The need for a new analytical tool to structure conceptual comparison*

The conceptual mapping approach emerged from a strong need to structure an explorative and otherwise hard-to-structure conceptual comparison. Specifically, there was a desire to systematically guide the comparison towards the similar, but not entirely identical method-specific concepts that would most benefit from a closer comparison. This need was especially pressing because breadth of the thesis topic made a comprehensive review of all related literature infeasible. Since no satisfying solution to this challenge could be found in earlier literature, the choice was made to develop a new analytical tool specifically for this thesis.

>> *Usefulness of conceptual mapping approach for structuring thoughts*

The most valuable contribution of the conceptual mapping approach to the results of this thesis was its helpfulness for structuring thoughts and providing direction during the conceptual comparison between data types. As outlined in **Section 4.2.2**, a conceptual mapping table asserts certain conceptual omissions, comparable concepts, conflicting terminology and aligned terminology. This was not only useful for performing an initial assessment of terminological and conceptual alignment in **Section 5.3**, but it also proved helpful in the construction of the conceptual mapping tables themselves; a process that was highly iterative. By checking the assertions made by each table, points of improvement could be easily identified, as shown in **Table 6.1**. In short, one of three situations can occur: (i) an assertion is true, requiring no further investigation; (ii) an assertion is false, meaning the table must be revised; (iii) it is unclear whether an assertion holds, in which case a closer comparison is needed to provide clarification.

This process of checking assertions allowed new iterations of the conceptual mapping tables to be made in quick succession, gradually creating a better overview of the relationship between different terms and concepts. Eventually, however, the distinctions between seemingly comparable concepts became too nuanced to express clearly within a tabular format. This is where this thesis opted to move on to a less structured conceptual comparison in **Section 5.4**.

All things considered, the conceptual mapping approach proved to be an effective tool to conduct a quick initial comparison of terminology and conceptual definitions, even if effectiveness diminishes once conceptual distinctions become more subtle.

Table 6.1: How assertions made by conceptual mapping tables highlight points of improvement at each iteration.

Assertion by conceptual mapping table	Possible point of improvement
Conceptual omission: In method A, no method-specific equivalent exists for concept X in method B	Look for concepts in method A that have a similar definition to concept X in method B. If found, this can be added to the table.
Comparable concepts (different methods): Concept X in method A has a comparable definition to concept Y in method B	Check if definition is truly the same, or if there are relevant differences in interpretation. If found, concepts should be disambiguated. Either by splitting the column of the conceptual mapping table into multiple sub-concepts, or by providing in-text clarification.
Comparable concepts (same method): Concept X and concept Y in method A have a comparable definition	If terms are no direct synonyms, determine where the conceptual distinction lies. Then disambiguate concepts either by updating the table or by providing in-text clarification in the same manner as described above.
Conflicting terminology: Term X in method A has a different definition than the same term X in method B	Check if definitions truly conflict. If so, this is a relevant finding that needs no further investigation. If not, terminology must be aligned instead, which is also a relevant finding.
Aligned terminology: Term X in method A and the same term X in method B have comparable definitions	Closely compare definitions if there is reason to believe that there are subtle differences in interpretation. If not, this is a relevant finding that needs no further investigation.

>> *Usefulness of conceptual mapping tables for presenting results*

The conceptual mapping tables were not only used as a preliminary tool to structure thoughts and guide the comparison process, but also as a means to present results and support later conclusions. Here, the usefulness of the conceptual mapping tables is less clear-cut. On the one hand, they provide a concise overview of the relationship between different terms and underlying concepts, which works well when those relationships are intuitively understood by the reader. On the other hand, when relationships between concepts are less straightforward, the table format leaves little room for clarification. Instead, in-text clarification has to be given separately from the table.

This proved to be problematic. Due to the large size of the conceptual mapping tables, a great number of concepts needed clarification at once before introducing the table. Because some of these explanations have to be lengthy, some clarifications are several pages removed from the table itself. The same goes for the discussion of implications that followed after the tables. To fully understand the results, the reader must continuously move back and forth between the table and the in-text elaboration located pages before and after the table itself. Not doing so presents a dilemma:

- (i) without the table as overview, the relationship between different pieces of in-text elaboration is quickly lost.
- (ii) without the in-text elaboration, the interpretation of the table and its implication may be unclear.

Seeing this, the author prefers a narrative-driven way of presenting results, as seen in the closer conceptual comparison of **Section 5.4**. This allows small topics to be addressed one-by-one, creating a natural flow in which argumentation, results and interpretation are placed closely together and in sequence. Ultimately, however, it is for the reader to decide which approach proved easier to interpret.

>> *Experienced limitations of conceptual mapping approach*

While the conceptual mapping approach turned out to be very helpful for structuring thoughts and moderately helpful for communicating results, some limitations were found that should be taken into account before applying it. Most importantly, the effectiveness of the approach depends on how well-defined the compared concepts are. If the definition of a term is ambiguous, its position in the conceptual mapping table is as well. This means extensive in-text elaboration is needed, which largely defeats the purpose of the conceptual mapping approach. This problem formed a major obstacle in writing this thesis until the choice was made to define each data type using a single primary literature source.

Another, more practical obstacle was that the conceptual mapping tables only allow so much detail to be included until they extend beyond the limits of a single page. In principle, the tables could be spread out over multiple pages, but this was found to greatly reduce the clarity that a single condensed overview table brings.

If these limitations are considered, however, the conceptual mapping approach proved to be a powerful tool for comparing terminology and conceptual definitions across multiple conceptual frameworks.

7 Conclusion

Integration between Material Flow Analysis (MFA) and Input-output Analysis (IOA) has so far been limited, despite earlier studies pointing out important similarities in purpose and approach: both analyze socio-economic metabolism from network- or graph-based perspective. To better understand what holds back integration, this thesis conducts a critical comparison of eleven distinct data types used within MFA and IOA. Unlike earlier studies, the focus is on terminological and conceptual distinctions that, as this thesis argues, are insufficiently understood because they are rarely explicitly articulated.

An important observation made during this comparison, is that clear and precise discussion of the data types in question is undermined in several ways, especially in a comparative context: (i) the distinction between MFA data, Supply-Use Tables (SUTs) and Input-Output Tables (IOTs) versus the broader methodological frameworks of MFA and IOA is often unclear; (ii) the terms MFA data, SUTs and IOTs not only describe generic data types, but are often used to refer to standardized implementations thereof (e.g. SNA/SEEA-based SUTs and IOTs); (iii) there is an overall lack of terminological alignment between MFA and IOA.

To address these terminological obstacles, this thesis clarifies distinctions and develops a method-neutral conceptual framework that provides a clearer alternative to conventional terminology, allowing multiple data types to be discussed simultaneously while acknowledging the conceptual similarities between them. This is not only helpful in the context of this thesis, it also provides a valuable basis to improve the conceptual precision of future methodological research.

With help of the method-neutral conceptual framework and a novel but effective conceptual mapping approach, various conceptual differences were found. Upon closer investigation, all appear to stem from one of three sources: (i) misalignment between system boundaries and disaggregation schemes, affecting what stocks, processes and flows are recorded; (ii) varying units-of-account, determining what characteristics of stocks and flows can and cannot be described by a certain data type; (iii) the requirement in IOTs for a one-to-one correspondence between products and producing industries, which limits the ability of IOTs to describe multi-output processes. Of these differences, the latter two are fundamental to the definitions of the data types, whereas misalignment between system boundaries and classification schemes, like terminological differences, could in principle be resolved by revising or adapting established conventions.

Most importantly, these findings indicate no insurmountable barriers to the integration or even unification between MFA data and Physical Supply-Use Tables (PSUTs), although this would require established terminological and methodological conventions to be challenged, particularly with respect to system boundaries and disaggregation schemes. As a result, the most promising path for integration is for the less standardized field of MFA to seek alignment with the already well-established conventions of the SNA and SEEA, and to adopt a PSUT structure for storing material flow data. Such integration may be desirable for various reasons: (i) a universally agreed on conceptual framework for analyzing material flows and production chains would greatly improve conceptual clarity; (ii) convergence to a single data type would enhance the accessibility, comparability and reusability of material flow data; (iii) alignment with the SNA and SEEA ensures compatibility with other types of statistical data; (iv) all of the above strengthen the case for systematically collecting statistical data on physical material flows, benefiting MFA and IOA practitioners alike.

Finally, the findings of this thesis reemphasize the need for integrated analyses of socio-economic metabolism, by highlighting conceptual differences between monetary and physical data that cannot be overcome by simply using conversion factors or models such as WIO-MFA. Based on the already strong terminological and conceptual alignment between monetary and physical IOA data, continuing efforts to integrate MSUTs and PSUTs into multilayer Hybrid Supply-Use Tables (multilayer HSUTs) seems to be the most promising direction for achieving this integration, although a lack of physical material flow data still poses an obstacle to their realisation.

8 Recommendations

This chapter condenses the key findings, conclusions, implications and research limitations of **Chapter 6** into a small number of actionable recommendations. **Section 8.1** starts with recommendations for future methodological development, followed by recommendations to MFA and IOA practitioners in **Section 8.2** and **Section 8.3** respectively.

8.1 Recommendations for Methodological Research

1. *Evaluate alignment between standards*

This thesis has shown that definitions, system boundaries and disaggregation schemes do not fully align between MFA standards (i.e. EW-MFA and MSA) and the SNA/SEEA used in IOA. Better understanding the degree of misalignment would facilitate the integration between MFA and IOA.

2. *Clarify differences between LCI data, MFA data and IOA data*

Earlier research by Pauliuk et al. (2015) and Myers et al. (2018) has shown that the shared directed graph structure of MFA data, SUTs and IOTs can also be used to describe LCI data. This points towards the potential for integration or unification of LCI data with the data types analyzed in this thesis, especially with HSUTs and HIOTs. However, such integration would require better understanding of the terminological and conceptual differences between them.

3. *Evaluate how data types are implemented in practice to create real datasets*

Before putting any significant amount of resources towards integration between MFA data and IOA data, practitioners from both fields should be thoroughly consulted and involved. This ensures that methodological developments align with real wants and needs of practitioners. If practitioners don't adopt new methods, there is no point in developing them.

4. *Explore how MFA data, SUTs and IOTs can be used outside their conventional analytical discipline*

The similarities between data types, especially between MFA data, PSUTs and to a lesser degree PIOTs, suggests they may in some situations be interchangeable. Exploring to what extent this is the case could open up new methodological possibilities.

5. *Continue the development of multilayer HSUTs and HIOTs*

Multilayer HSUTs and HIOTs have two substantial benefits over other data types: (i) the relationship between layers can be used as an additional balancing dimension, improving the robustness of both physical and monetary data. (ii) the combination of multiple units-of-account allows them to comprehensively capture flows that are necessarily excluded in single-layer monetary or physical data (e.g. unpriced waste flows and services).

6. *Develop overarching conceptual framework for Industrial ecology*

Developing a common language to discuss the shared elements between MFA, IOA and LCA would improve the precision of methodological discourse when comparing or integrating these methods. This could also be helpful for didactic purposes. A neutral conceptual framework could achieve the following:

(i) highlight the shared basic system structure of MFA data, SUTs and IOTs (and LCI data)

(ii) clearly separate the independent steps such as data collection, data processing and data analysis within the modeling frameworks of MFA, IOA and LCA.

(iii) show where analytical steps of MFA, IOA and LCA fulfill the same functions and could potentially be used interchangeably.

8.2 Recommendations to MFA Practitioners

1. *Clearly separate independent steps within the analytical framework of MFA*

Distinguishing between different steps such as data collection, data processing and data analysis would improve conceptual clarity, facilitate more precise methodological discussion and highlight the functional overlap of MFA with other methods.

2. *Clearly distinguish between bulk-MFA data and material-specific SFA/MFA data*

Although this distinction is often clear from context, it seems wise to eliminate any ambiguity considering the far-reaching implications of differences in unit-of-account. A wider adoption of the terms Substance Flow Analysis (SFA) data and bulk-MFA data would achieve this.

3. *Aim to ensure traceability and monofunctionality where possible*

Modeling traceable and monofunctional processes maximizes the (re)useability of MFA datasets for analytical purposes such as origins analysis and footprint analysis. So, where data availability allows, disaggregate processes and flows in such a way that:

- (i) every process has a single unique inflow or a single unique outflow to which all other flows can be traced;
- (ii) every process corresponds to a single functional product output. Defining explicit market processes helps achieve this

4. *Seek alignment with established statistical standards*

Contribute to methodological integration by avoiding unnecessary misalignment with established statistical standards and classification schemes (e.g. SNA/SEEA, ISIC, CPC, HS, SITC).

5. *Formalize conventions and best-practices in versatile standards*

A lack of standardization within the field of MFA does not only limit comparability and reuseability of MFA datasets, it also holds back clear and precise methodological discourse. The use of the SNA and SEEA in IOA shows that standardization does not necessarily lead to a significant loss of versatility if the standard considers the variety of practical needs and capabilities of its users. Unlike the existing MFA standards of EW-MFA and MSA, aim to standardize how concepts are implemented, not if they are implemented^[1].

6. *Consider adopting a PSUT format*

Physical Supply & Use Tables (PSUTs) provide a versatile, largely standardized framework for recording material flows within the economy that is aligned with existing statistical standards including the SNA, SEEA and EW-MFA. If small, they can be visualised in network diagrams like MFA data, or presented as tables if they become too large. They can also be converted to or integrated with other data types such as PIOTs or (multi-layer) HSUTs using established methods, making them useful for a wide variety of purposes.

[1] For example, specify classification schemes that work at multiple levels of disaggregation (e.g. as in the SNA/SEEA) instead of rigidly prescribing a predefined level of disaggregation (e.g. as in EW-MFA and MSA). Or, specify how to define the boundaries of the economy, while allowing for system boundaries that extend beyond these economic boundaries.

8.3 Recommendations to IOA Practitioners

1. *Clearly separate independent steps within the analytical framework of IOA*

Distinguishing between different steps such as data collection, data processing and data analysis would improve conceptual clarity, facilitate more precise methodological discussion and highlight the functional overlap of IOA with other methods.

2. *Clearly distinguish between PSUTs and PIOTs with different units-of-account*

PSUTs and PIOTs may either be expressed in mass units (e.g. tonne), material-specific mass units (e.g. tonne Fe or tonne CO₂) or energy units (e.g. MJ). Considering the far-reaching implications of differences in unit-of-account, it seems wise to eliminate this ambiguity. Either by explicitly communicating the unit-of-account, or by revising the naming conventions of PSUTs and PIOTs.

3. *Clearly distinguish between generic IOA data and standardized IOA data*

Most SUTs and IOTs are produced according to the guidelines laid out in the SNA and SEEA. However, this is not the only way to create a mathematically valid and useful dataset. To acknowledge the flexibility of SUTs and IOTs when discussing these data types, it would be helpful to explicitly distinguish between generic SUTs and IOTs and SNA/SEEA-based SUTs and IOTs.

4. *Aim to ensure traceability and monofunctionality where possible*

Modeling traceable and monofunctional processes maximizes the (re)useability of SUTs and IOTs for analytical purposes such as origins analysis and footprint analysis. So, where data availability allows, disaggregate rows and columns in such a way that: (i) every product or residual is either produced or consumed by a single unique sector, ensuring traceability; (ii) every process corresponds to a single primary product output.

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