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4 **Title:** A Bottom-up Ontology-based Approach to Monitor Circular Economy: Aligning User Expectations,
5 Tools, Data and Theory

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19 **Keywords:** circular economy, ontology, transition management, ontology alignment, Circular Economy
20 Monitor, industrial ecology

21 **Abstract:** With circular economy being high on governmental agendas, there is an increasing request from
22 governing bodies for circularity measurements. Yet currently existing macro-level monitoring frameworks
23 are widely criticized for not being able to inform the decision making. The reasons behind their failure
24 stem from a lack of consensus on terminologies and definitions among scholars, politicians and practition-
25 ers, a lack of supporting data and tools and, consequently, a lack of transparency and trustworthiness. To
26 fulfill those needs, a bottom-up approach to build a shared terminology is suggested by involving macro-
27 framework users within a government, data providers and tool developers. Their expertise and expectations
28 for monitoring the transition are elicited through the process of formal ontology development and alignment.
29 The ontology development experiment builds upon a use case of the Amsterdam Circular Economy Monitor
30 (2020). First, four ontology development approaches are used to create a theory-centered, a user-centered,
31 a tool-centered and a data-centered ontology. The ontologies are later compared, merged, and aligned with

each other to arrive at one single ontology. The notes taken during the process are used to provide a detailed discussion on common concepts, identified conflicts, and gaps in monitoring expectations between the monitor users, data, tools, and the latest theory.

1 INTRODUCTION

The global mega-trend of resource scarcity in combination with rapidly changing demographics (Retief et al., 2016) increases the pressure for the need to transition towards a circular economy (CE). The trend is reflected in the growing amount of policy documents that put CE high on the agenda: from national and supranational plans (The European Commission’s Circular Economy Action Plan ((European Commission, 2020), Circular Economy Promotion Law of the People’s Republic of China (PRC, 2008)) to city scale strategies (e.g. Amsterdam Circular Strategy 2020-2025 (Gemeente Amsterdam, 2020), London’s Circular Economy Route Map (London Waste and Recycling Board, 2017)). The next step after the targets are set and actions are listed, is tracking progress and monitoring their effectiveness.

While separate industries are able to set up monitoring mechanisms that concern their own material purchasing and disposal patterns and (in)direct impacts, governments hold the power to set up overarching monitoring systems that, although have the primary goal to inform government officials themselves, may also serve and secure private efforts to accelerate the transition. One of the powers governments hold is access to large-scale data from multiple sources in their area of power that can provide an overarching baseline model as a general benchmark against which the transition can be monitored. To avoid misplacing the impacts or wasting resources on low impact measures, they are increasingly searching for macro-level monitoring frameworks (Harris et al., 2020; Saidani et al., 2019; Parchomenko et al., 2019) that would not only describe the status quo but also provide direction for future decision making (Planbureau voor de Leefomgeving, 2021).

Yet currently existing frameworks are widely criticized for being too aggregate and therefore generic (Haberl et al., 2019), disconnected from environmental impacts, not able to measure reduction or prevention (Harris et al., 2020) and not being related to concrete targets nor accompanying policies (Friant et al., 2020). Moreover, top-down macro frameworks require standardized data collection and reporting systems that involve multiple stakeholders which are often too hard to implement (Harris et al., 2020). The process of decision making and monitoring of success is further exacerbated by the lack of agreement on what it is exactly that the transition towards a CE is supposed to achieve (Kirchherr et al., 2017; Corona et al., 2019) and what can and should be achieved by policy interventions (Friant et al., 2020). Policy decisions on resource management do not only affect the place and time where and when policies are made but extend far beyond the chosen territory and time frame due to the existing networks of resource flows (Furlan et al., 2020; Korhonen et al., 2018).

To overcome the challenges that top-down monitoring frameworks face at this stage of the transition, we suggest to begin with a bottom-up approach and first consolidate the available data, existing theory and practical concerns of the decision makers. We argue that aligning terminology, capabilities and expectations helps to expose and therefore overcome the limitations of current monitoring frameworks. Therefore, the objective of this publication is to demonstrate how an ontology creation process can facilitate the exposure of data and knowledge gaps and potential conflicts. Additionally, we illustrate how this process helps identifying the core concepts on which a monitoring framework can practically be built.

A use case from the city of Amsterdam in the Netherlands has been chosen to evaluate and demonstrate how the available data, tools, user expectations, and theories behind a circular economy monitor (mis-)align with each other. The city has an ambition “to be 100% circular by 2050, with an intermediate target of a 50% reduction in primary raw materials consumption by 2030” (Gemeente Amsterdam, 2020). To measure the progress towards its goals, Amsterdam is currently building a Circular Economy Monitor (CEM) which should serve as a powerful data infrastructure for CE transition monitoring and decision support.

2 THEORY

Monitoring a transition is often entrusted to a series of indicators that allow quantifying the speed of progress towards the desired state. However, despite the abundance of indicators that have been created to monitor the CE transition, an increasing number of papers are being published that discuss their limited utility (Harris et al., 2020; Morsetto, 2020; Saidani et al., 2019; Corona et al., 2019; Parchomenko et al., 2019; Korhonen et al., 2018). Especially macro-level indicators and monitoring frameworks seem to be lacking success due to a few commonly repeating underlying causes.

The most prominent remark repeated in multiple reviews is the lack of consensus on CE terminologies and definitions among scholars, politicians and practitioners (Homrich et al., 2018; Kirchherr et al., 2017). Harris et al. (2020) noticed that some scholars regard the main aim of CE to achieve economic prosperity, followed by environmental quality, whilst others perceive the aim in the opposite order. Parchomenko et al. (2019) have made an attempt to list all relevant CE elements and found that neither the list of elements can be robustly grounded in the existing literature, nor the precise meaning and distinction between them. Korhonen et al. (2018) take the critique of the field even further by stating that “the scientific and research content of the CE concept is superficial and unorganized. CE seems to be a collection of vague and separate ideas from several fields and semi-scientific concepts.”

The other group of remarks is related to the technical challenges. While the existing macro-level frameworks (or their modifications) all together are likely able to answer all CE goals, there is no single integrated methodology that can integrate all required parts (e.g. assessing scarce resource input, emission levels, material losses, product durability, local jobs, etc.) into a single study (Corona et al., 2019). At the same time, the wide majority of macro-level CE indicator frameworks are not linked to any tool that is able to calculate them and remain mostly described textually (Saidani et al., 2019). And eventually, the requirements cannot be met by the data that is available to support the frameworks (Harris et al., 2020).

Finally, the current indicators lack transparency and trustworthiness to be applicable in decision-making (Saidani et al., 2019). Material or value circulation are measured as a proxy for environmental impact despite the limited evidence that products designed for increased circularity have increased environmental performance, particularly from a macro-perspective (Saidani et al., 2019; Parchomenko et al., 2019; Harris et al., 2020). For the lack of better alternatives, existing CE targets do not necessarily promote a circular economy but focus on recovery and recycling (Morsetto, 2020).

Differently than authors who suggest that “constructs involved in the CE literature still need to be further refined and a more homogeneous nomenclature should be applied” (Homrich et al., 2018), we suggest that at this stage of the transition all the efforts to systematize knowledge (and this way monitor progress) have to strive for maximum flexibility and adaptability to new findings and improved definitions.

The technology to support this heterogeneous approach is in principle available and can be based on Seman-

tic Web standards, ontologies, shareable linked data repositories and other e-Science technology. To support this technically, it is necessary that distant communities of practice use semantic metadata (Scheider et al., 2017). One of the key technologies for organizing a conceptual world is ontology engineering (Kumazawa et al., 2009).

An ontology in its basic sense can be understood as a controlled vocabulary in which a certain world, domain or model is described. It provides names to the most important concepts, their synonyms, and antonyms, and describes which properties are allowed and expected and how these concepts relate to each other. It is an information technology intermediary that can be understood both by people and computers. Formalizing a concept into an ontology makes it machine readable, which facilitates data exchange, allows automated reasoning and ensures concept, data and metric reusability and interoperability.

Every model implicitly uses an ontology but few of them are explicitly formalized beforehand. Every data collection is based on its implicit ontology and often recorded as explicit metadata. Monitoring applications typically make use of a relational database which can be converted into an ontology (Zedlitz and Luttenberger, 2012; Munir and Sheraz Anjum, 2018). In turn, humans who use data and relational databases have specific questions in mind that are expressed using domain-specific terminology. The terms used may have explicit definitions grounded in theory and shared between all domain experts or they may be used interchangeably and change meaning depending on the context.

If the domain knowledge is well grounded in theory and well established, the implicit ontologies of data, tools and users are also implicitly aligned. However, if a research field is still emerging or highly contested, there is a risk of misalignment that leads to a multitude of problems (Kumazawa et al., 2009). Even the most comprehensive tools risk not being used if users do not find how provided information helps to answer their specific questions. If a database structure does not align with data semantics, the data risks to lose its utility during its processing and conversion. Not using terms that are grounded in theory causes the systems to be short-lived due to their low interoperability and replicability in different contexts. Finally, if the lack of alignment is overlooked, wrong conclusions can be made stemming from the conflicting terminology.

Since Holsapple and Joshi (2002) have suggested an ontology development process as a means to support collaboration between different disciplines, it has been used in a variety of settings including water-energy-food nexus (Kumazawa et al., 2009), defining projects and scenarios for an integrated assessment modeling of agricultural systems (Janssen et al., 2007), knowledge management within e-government services (Fraser et al., 2003), integrated highway planning (France-Mensah and O'Brien, 2019) and a multitude of others.

Although the body of literature on Circular Economy has been growing since Brundtland report (1987) and since 2010's (Calisto Friant et al., 2020) increases exponentially, the use of ontologies is rarely included into the discourse. While a SCOPUS search of the term "Circular Economy" returns 9195¹ results, only 28 of them mention the word "ontology" in the title, keywords or abstract and only 11 of them do actually focus on describing, developing or evaluating ontologies (Capelleveen et al., 2021; Pacheco-López et al., 2020; Mbolli et al., 2020; Fernández-Acero et al., 2019; Gligoric et al., 2019; Sauter et al., 2018; Martín Gómez et al., 2018; Sauter and Witjes, 2017; Pauliuk et al., 2016; Vasantha et al., 2015; Olivier et al., 2015). Table 1 shows an overview of the domains and purposes of those 11 ontologies. To date, there has been no published attempt to use formal vocabularies in constructing circularity metrics. Likewise, to the best of the authors knowledge, no ontology exists that aims to support policy decisions in the transition towards a CE.

It is important to notice that none of the described ontologies (except for the European Waste Classification

¹as of 5th March, 2021

taxonomy) have been published along with a scientific paper that describes them. This automatically prevents their reuse and further development. Yet reusing existing ontologies from the same or even adjacent disciplines is the most common advice in ontology development literature.

Pauliuk et al. (2016) is the only of the analyzed articles that have published enough details to recreate the ontology exactly as suggested by the publication. The ontology proposed by Pauliuk et al. (2016) is also the only one that facilitates high-level information exchange, which aims to support interdisciplinary research and can be used on a macro level. For these reasons their ontology is further used and developed in this paper.

3 METHODS AND DATA

Holsapple and Joshi (2002) have described 5 general ontology development frameworks: inspirational, inductive, deductive, synthetic, and collaborative. The frameworks differ in terms of the starting point (seed) for the ontology creation. Even if the domain and purpose of the ontology is the same, dependent on the method used to create them, it may deliver radically different results. Therefore a hybrid and iterative approach is recommended until the ontology is considered application-ready.

For this paper, four different ontology creation approaches have been used based on the Amsterdam CEM use case: user-centered (collaborative), data-centered (inductive), tool-centered (inspirational), and theory-centered (synthetic). The four created ontologies are then compared and merged with each other in an iterative manner to arrive at a single ontology that would satisfy all requirements as closely as possible. Ideally, all four should be easily mappable to each other. That would mean that there is a clear correspondence between what the users of a circular economy monitor wish to know, what a circular economy monitoring and decision support tool is able to provide, which data is available, and what is backed up by scientific theory.

The more overlapping concepts can be found between the four initial ontologies, the better they are aligned. Therefore, the notes on ontology mapping, alignment, and merging of concepts are used to discuss the CE terminology, underlying assumptions, data and knowledge gaps. Table 2 explains the four approaches in further detail. All four ontologies are available in a public repository², further details about their development are available in the supporting material.

The CE ontology resulting from the described development process is an open source initiative that is used as part of the Amsterdam CEM currently under development by the Amsterdam Municipality CTO Innovation office and geoFluxus BV. The ontology is tailored to the Amsterdam case and therefore would need to be revised and adjusted to fit a different decision making context with different underlying datasets and different circular economy goals and ambitions.

The four ontologies that have resulted from the theory-, tool-, user- and data-centered approaches have been combined into one by performing the following steps:

1. All entities and axioms from the four ontology approaches have been copied, retaining their original IRI into an empty ontology file. This way those entities that had the same short names did not get merged into the same entity.

²<https://github.com/rusne/ImpactOntology/tree/master/ontologies>

Table 1: Overview of all publications returned by SCOPUS that focus on describing, developing or evaluating ontologies in relation to a circular economy

Publication	Domain	Purpose					Available for reuse	Scale
		Waste-to-resource-recom-mender sys-tem	Internet of Things	Product or ma-terial pass-port	CE busi-ness model sup-port	Data and in-for-mation ex-change		
Capelleveen et al. (2021)	European Waste Catalogue	+					Yes	-
Pacheco-López et al. (2020)	Waste Treatment Processes	+					No	Meso
Mboli et al. (2020)	Product life cycle monitoring		+		+	+	No	Micro
Fernández-Acero et al. (2019)	Nannochloropsis gaditana microalgae	+					No	Micro
Gligoric et al. (2019)	Product passport		+	+	+	+	No	Micro
Sauter et al. (2018)	Building material passport	+		+		+	No	Micro
Martín Gómez et al. (2018)	Eco-industrial parks	+			+	+	No	Meso
Sauter and Witjes (2017)	Product passport for textiles			+		+	No	Micro
Pauliuk et al. (2016)	Socioeconomic metabolism					+	No	Macro
Vasanth et al. (2015)	Product-service systems				+	+	No	Meso
Olivier et al. (2015)	Equipment maintenance					+	No	Meso

Table 2: The four ontology development approaches used to develop an ontology for the Amsterdam CEM

User-centered / Collaborative approach	Data-centred / Inductive approach
Collaborative approach focuses on eliciting domain knowledge from multiple experts that have different viewpoints towards the subject. In our case it starts from eliciting the requirements of the future system’s users in the form of informal competency questions. The questions act as requirements for the axiomatization of the ontology. The questions have been elicited in a form of written user interviews where 18 respondents from the Amsterdam Municipality have been asked what they expect from a digital CEM.	Inductive approach is based on examining a specific case in the domain which can be applied to other cases in the same domain. Therefore a data-centered ontology is created based on the analysis of data XML schema, available metadata, and interviews with the specific dataset providers. The two datasets considered for this experiment are a national waste data registry and a port import/export data that together represent a large part of material flows relevant to the CEM.
Tool-centered / Inspirational approach	Theory-centered / Synthetic approach
Inspirational approach stems from an individual or a group of individuals using their views on the domain of interest to create an initial ontology. Thus the tool-centered ontology stems from a tool-developers perspective on the problem and its abstraction in a relational database. A Geodesign Decision Support Environment (Arciniegas et al., 2018; Remøy et al., 2019) has been used to kick-start the Amsterdam CEM. Therefore, its relational database has been considered as a starting point of the inspirational approach for an ontology.	Synthetic approach considers existing ontologies a starting point for a new ontology creation. The theoretical basis for the monitor stems from socio-economic metabolism (SEM), which is an adjacent domain to the Circular Economy. Based on the previously elaborated review of existing ontologies in the CE domain (Table 1), the one developed by Pauliuk et al. (2016) has been selected as the most suitable one to be reused as an initial input. This ontology integrates multiple ontologies from the SEM study domain this way allowing efficient data and knowledge exchange between different studies.

2. Entities that have the same short names have been investigated to decide whether they are indeed the same entities and can be merged into one or if they need to be renamed to distinguish between the different concepts. E.g. `Activity` from the tool-based ontology and `Activity` from the data-based ontology actually refer to two non-overlapping concepts and therefore the latter has been renamed into `HarbourActivity`).
3. Entities that do not have the same short names but anyway refer to the same concept have been aligned in the hierarchical order by subsumption or equivalence. Entities that after alignment became subclasses of broader classes were checked for the integrity of the inherited axioms.
4. Entities that refer to opposing concepts have been disjoint. *Part-of* relationships have been introduced by `contains` and `belongsTo` object properties.
5. Similar entities that describe neighboring concepts have been grouped together by making them subclasses of a single superclass. If any of the axioms available on the subclass level were true to the superclass level, they were moved to the superclass and automatically inherited by the neighboring concepts.
6. Finally, a HermiT 1.4.3.456 reasoner has been used to debug the ontology and it has been confirmed as coherent and consistent.

A detailed list on all performed actions and alignment process can be found in the supporting literature.

The alignment process has been performed by the authors of this paper in consultation with the data providers, tool developers and representatives of the Amsterdam municipality. The consultations happened in the form of informal discussions.

4 RESULTS

The alignment process has resulted in a coherent and consistent ontology that hosts 161 classes, 64 object properties, 87 data properties, and 781 axioms. Not all classes in the ontology could be defined with the same level of detail even after consulting their creators. The resulting ontology is not application ready and rather describes the first attempt of alignment which requires further iterations as described below.

In general, four categories of classes could be distinguished dependent on the process that is required to define them and which related steps are still missing before the ontology can be used to support the Amsterdam CEM. Those four categories closely relate to the different types of knowledge gaps and ambiguities that could be identified during the ontology alignment process. Following is a short description on each of the four categories.

4.1 Core Concepts

Core Concepts are those classes that describe the informational and data structure as the basis of the CEM. Core Concepts can be found in all four of the underlying ontologies even if they are named differently (e.g., the tool-centered ontology assumes that flows connect actors instead of connecting processes as in case of the theory-centered ontology). The definitions of these concepts are strongly grounded in theory and can be

aligned with the available data. They are well understood and requested by the users, and therefore can be explored using the CEM tool.

The goal of the combined ontology is the representation of the past, current and future material flows and stocks and their relevance to the transition towards the circular economy. Therefore the core concepts provide a minimal amount of entities necessary to describe material dynamics. The core concepts are definite, explicit and exhaustive. The combined ontology extends the core concepts defined by Pauliuk et al. (2016). Next to having the concepts of Flow, Process, Stock, and Service, it introduces the concepts of Actor, Destination, Origin, InputFlow, and OutputFlow. Figure 1 summarizes which classes of the combined ontology are considered the Core Concepts.

The need for an Actor class arises from 1) lack of specifications in data about what processes certain actors perform; 2) the need to know who is responsible for the decision making regarding the content and direction of output and input flows. Therefore, an Actor is defined as an institution, organization, company, a group of people (e.g. households), etc. that participate in processes and services and whose behavior and decisions need to be influenced to change the content and context of flows, processes and stocks. Actors have a context (location) which determines which institution is able to change the context conditions or policies to change the behavior of an actor. Actors may own stocks.

In SEM definition, stocks can be involved in events, while in the tool-centered ontology describes a stock as the amount of materials that have not changed their location in a given period of time (in case of the GDSE the period is a calendar year). Therefore, to align the ontologies, the tool-centered definition of a stock is considered a subclass of the `sem#stock` and has been renamed into an `tool#IdleStock`, defined as a set of objects that have not been involved in any event given a chosen period of time.

`Destination`, `Origin`, `InputFlow`, and `OutputFlow` allow modeling situations in which the available data does not allow definite modeling of flows. E.g., in cases when only aggregated numbers are known for the total amount of products exported from a certain area without having further detailed information about how they are distributed afterwards. In the original GDSE application, for instance, such data would be registered as a flow from a known actor (or a group of actors) to an unknown destination. Although incomplete, such data still allowed simulation of solutions and circular economy strategies and assessment of their impacts.

4.2 Observational Properties

Observational properties are those classes that describe the properties of core concepts and have intrinsic values and relationships. They are axiomatic, therefore not disputable (although their values may be disputable, the meaning of the properties themselves is not questionable). Observational properties are definite. Like the name suggests, observational properties refer to the values that can be observed (e.g. stock or actor location, material content or quantity, observation source). They can be registered using different units and may differ under different conditions, but a conversion to another unit or measure is possible if the conditions are known (e.g., flow content can be expressed on product, material or substance level of detail if enough information is provided). Observational properties are used to provide additional information on the core concepts. Observational properties can always refer to the source of an observation. If an observation does not have a direct source and has been extracted by combining different data sources, it can refer to a model which has been used to obtain the value.

Observations may be part of either an objective biophysical reality that exists independently of the individual observer, or a social-legal reality that is constructed by humans (Spash, 2012; Fischer-Kowalski and Weisz, 1999). When the data used to study material flows and stocks comes from legal registries and reporting systems, the observations are always social-legal and might or might not reflect the biophysical reality as well.

Observational properties can belong to one of the four subclasses dependent on what they are describing: content, context, effect, or an observation itself. Figure 2 summarizes which classes of the combined ontology are considered an **Observational Property**. Classes that describe observational properties were mostly found in the data-centered ontology.

4.3 Debatable Properties

Debatable properties, differently than the observational ones, do not have fixed values or relationships, their definitions may change over time and cannot be considered axiomatic. Those definitions need to be clearly defined by referencing a certain standard or by creating a set of ontological rules.

Debatable properties most likely may not be found directly in data and need to be derived. They are typically not quantitative. Once the values of the debatable properties are known, they cannot be easily converted from one system to another by using a common knowledge unless the conversion rules are provided. In cases when data schema uses debatable properties, their suitability for monitoring purposes requires a debate nevertheless. E.g., both tool-centered and user-centered ontologies use an **Activity** class that is meant to group actors according to their core activities that result in certain material demands. The GDSE tool has been using NACE Rev. 2 Statistical Classification of Economic Activities to group actors into activities (Furlan et al., 2020). However, the classification covers only economic activities, therefore actors whose material demands do not arise from an economic activity (household consumption, public infrastructure works, etc.) are not covered by the classification. Moreover, since the purpose of the NACE taxonomy is not related to the circular economy, this grouping can lead to arbitrary aggregations.

Before (re)using the ontology the debatable properties should be debated and agreed upon with all relevant stakeholders (domain experts and system users) and their definitions must be made available. Debatable properties can be split into taxonomies and denotations. Taxonomies are hierarchical arrangements of multiple terms that specify the same concept in greater detail. Denotations are terms that require a definition provided by using ontological rules for defined classes. Both taxonomies as denotations do not have to be invented from scratch and ideally would be reused referencing a definition in an established domain such as macroeconomics, process engineering, industrial engineering, etc.

Figure 3 summarizes which classes of the combined ontology are considered a **Debatable Property**. Classes that describe debatable properties were mostly found in a user-centered ontology.

Some classes can have both taxonomy and denotation subclasses. E.g., **Material** class is a property that requires a material taxonomy to be used to describe the content of stocks. However, such properties as **BioBasedMaterial**, **DemolitionWaste**, **EndOfLifeMaterial**, are denotations that should refer to certain members of the material taxonomy.

4.4 Specific Properties

Specific properties are neither observable nor debatable. They are specific to a certain user or a group of users. They describe relationships between classes based on particular non-axiomatic definitions. Since they are clearly based on personal (or group) opinions, they cannot be disputable either. They need to always refer to the author(s) of property values and definitions.

Targets, aims, goals, and challenges are typical examples of specific properties as different user groups can have different interpretations of both the definition and the value of such a property. Such properties can change with time or when different people take up the same functions, e.g., in the case of governmental targets.

The difference between specific and debatable properties is that debatable properties need an agreement between different groups of users or stakeholders, while specific properties do not need to be agreed upon. Specific properties define variables that can be decided upon - they are like parameters of monitoring and decision support that can be played around with. Debatable properties, on the other hand, are variables of the system that should not be changed to get better monitoring results. E.g., a target for local food production can be changed to check how easily it can be met, but the boundary of "local" should not be changed to easier meet the set target. A specific case study area can be easily expanded by a study group, but changing administrative units would require a complicated process involving multiple stakeholders.

Figure 4 summarizes which classes of the combined ontology are considered a **Specific Property**. Classes that describe specific properties were mostly found in user-centered and tool-centered ontologies, which is expected from the inspirational and collaborative ontology development frameworks.

5 DISCUSSION

The theory-centered, user-centered, tool-centered, and data-centered ontologies can all be assigned to the circular economy domain. However, the alignment process has exposed that the correspondence between the ontology classes is rather limited. Here below we discuss the possible underlying reasons for the lack of overlap between the classes identified using four different ontology development approaches.

5.1 Correspondence

Monitoring the transition towards a Circular Economy is first of all concerned with representing material flows and stocks and their relevance to the transition. This assumption can also be confirmed by the observation that the core concepts that are primarily based on this representation have been identified in all four of the underlying ontologies. The core concepts have been aligned by either merging repeated concepts into one (specifically Flow, Process and Actor) or by subsumption.

There are a few groups of concepts that are semantically close but do not have a clear direct correspondence with each other due to lacking definitions and axioms. One outstanding group relates to the material content of the stocks and flows. Data-centered ontologies describe the material content of flows using international classifications (taxonomies) of wastes or products that do not always contain a specification of materials that constitute those waste or product streams. However, monitor users ask for information about specific groups

of materials (e.g., raw, food, bio-based, end-of-life materials). Meanwhile a tool-based ontology uses a generic **Material** class further enriched by such properties as **isAvoidable** and **isHazardous** and a **Composition** class that distinguishes between **Product** or **Waste** subclasses based on the underlying data. Finally, such stock properties as chemical structure, heat capacity, elemental composition, etc. suggested in the SEM ontology are not available in the data and are not mentioned by the users.

Another group of close concepts relate to the location and geographical extent. Data typically describes the geographical location of actors without explicitly specifying whether that is the actual location of material stocks. Monitor users are interested in comparative statistics that use vaguely defined geographic extents such as local, city-scale, built environment, etc. And the tool allows using administrative levels to group actors or flow origins and destinations.

Both material and geographical properties can be aligned between the ontologies if:

1. Experts and users are involved in the ontology creation process and can provide their suggestions for the correspondence between the observational and debatable properties.
2. Providing such a correspondence can easily become a tedious task if each member of the taxonomy needs to be manually matched with their material content. E.g., the European Waste Catalogue is made up of approximately 650 different codes, and the Harmonized System Nomenclature used in harbor declarations comprises about 5,000 commodity groups. Therefore such correspondence tables should be developed as a common effort and shared together with the available ontologies by the CEM creators.
3. Data providers are involved in the ontology creation process and can provide sufficient metadata that allows semantic matching of the entities available in the data to those asked by the monitor users.

5.2 Terminology Conflicts

Most of the conflicts could be resolved by renaming the classes to better specify how they differ from each other (e.g., **tool#Stock** has been renamed to **tool#IdleStock** and became a subclass of **sem#Stock**, **data#Activity** has been renamed to **data#HarbourActivity** and became a subclass of **tool#Activity**).

Instead of hard terminology conflicts, some semantic heterogeneities (differences in interpretation of the meaning of data) could be found between the ontologies. The most prominent one is the confusion between an activity and a process. The tool-based ontology considers flows as material movements between actors that all carry out a certain (economic) activity. Thus, on an aggregated level it is possible to analyze the material flows between activities and identify how each of them contribute to the waste production (Furlan et al., 2020). While some of the activities could be considered processes in the SEM ontology (mining, quarrying, manufacturing, transporting, etc.) others do not describe what happens to the materials, only what causes them to be moved or discarded (catering services, recreational activities, education, etc.). From the user interviews such terms as consumption, production, raw material extraction, material use are used to question what needs to be changed to accelerate the transition. None of these terms appear in the data-centered ontology, therefore without a clear distinction between a process and an activity, those questions cannot be answered.

This confusion could be resolved by making the following distinction between the two concepts: **Process** - an event that modifies properties of a participating stock. **Activity** - a property of an actor which describes

the reason an actor is carrying out a certain process.

Thus, a process mostly defines what happens to a stock, e.g., a stock of waste is sorted, a stock of food products is transported to another country, etc. In some situations an activity and a process might be the same if, for example, a transportation company (**Actor**), provides transportation services (**Activity**) to transport (**performsProcess**) some goods (**Stock**). However, if a restaurant discards food waste, then its activity is catering while the process is waste disposal.

5.3 Expectation Gaps

Expectation gaps can be observed by analyzing the concepts that appear only in one of the four ontology approaches without having close correspondences in the other ones. It is especially relevant to analyze non-corresponding concepts that appear in the user interviews as it means that the chosen data, tools, and theory are not sufficient to answer the questions raised by the ones who need to implement policies to advance the transition. The concepts that could be found only in the user interviews could be roughly divided in two groups:

- Concepts that relate not only to observing the state of flows and stocks but to the interpretation of what values and impacts they actually have: **SocialImpact**, **IndirectEmission**, **EcologicalValue**, **EconomicValue**, **SufficientProgress**. All of these concepts are specific concepts that ask a user to provide one's own interpretation and definitions, however, the currently available entities in the ontology are likely not enough to provide definitions for the mentioned concepts.
- Concepts that relate to the means that can accelerate the transition, in particular **Barrier**, **TransitionGoal**, **CircularProject**, **ValueChainInnovation**. These concepts relate to the solutions, aims, and challenges of the tool-centered ontology. However, the tool-centered ontology (and thus the tool itself) provides limited definitions and relations between the concepts which are left to the free interpretation of a user.

From the theory and data perspective, a concept that goes unmentioned by the users and not implemented in the tool is services. Pauliuk et al. (2016) define services as phenomena "where the changes of the consuming unit are small compared to the energy and material throughput of the producing activity". Although not directly involved in the material flows, services (e.g., transshipment or brokerage services) do have influence on where the material flows are directed, which processes are applied, and what is the size and composition of the participating stocks.

5.4 Missing concepts

The resulting overarching circular economy ontology is rather an initial attempt than a complete representation of the circular economy domain. The number of entities is limited to those that have been found in the four underlying ontologies. Therefore it is expected that every time the ontology is used in a new monitoring and decision making context, it will need to be updated to meet different user needs, increased knowledge base, tool requirements and available data fields.

Based on the requirements from the related literature Morseletto (2020); Corona et al. (2019); Suárez-Eiroa et al. (2019); Kirchherr and van Santen (2019) for the validity of circularity metrics, future work on expanding the current ontology should consider adding the following concepts:

- More quality properties that describe the quality of observations, such as data granularity, accuracy of measurements, certainty, and model sensitivity;
- immaterial flows of assets that play an important role in the circular economy, especially financial flows, energy flows and information flows throughout full supply chains;
- concepts related to environmental impacts, especially pollutants and GHG emissions;
- utility and durability of stocks;
- concepts that relate to social well-being and employment at all skill levels;
- business models and value creation, capture and distribution;
- fiscal, legal and organizational contexts.

6 CONCLUSIONS

To understand whether an ontology development process is able to benefit CE monitoring efforts, four approaches have been used to create four separate ontologies that were later compared, merged, and aligned with each other to arrive at a single integrated ontology. The notes taken during the process have been used to provide a detailed discussion on common concepts, identified conflicts, and gaps in monitoring expectations between the monitor users, data, tools, and theory. The resulting ontology entities could be divided into four major groups: core concepts and their observational, debatable, and specific properties.

The common concepts identified in all four ontology building approaches have led to the formulation of the core concepts for monitoring the transition towards a circular economy. The core concepts were stocks, flows, and processes - as suggested for the practical ontology for socioeconomic metabolism by Pauliuk et al. (2016) - with actors as an additional concept identified in the other three approaches. Actors participate in processes and services and their behavior and decisions need to be influenced to change the content and context of flows, processes, and stocks.

Although no acute terminology conflicts have been identified by aligning the four ontologies, the alignment process has proved to be beneficial in identifying and resolving confusing or ambiguous terms. A number of classes need subsequent iteration of ontology development before the ontology can be used in an application. Specifically, the debatable properties such as taxonomies and denotations need consensus from the monitor users and CE experts on their choice and precise definitions. Especially debatable properties would benefit from reference to existing standards related to CE domain, e.g., existing ISO standards or established vocabularies of industrial ecology. Specific properties require explicit references to their authors and their definitions.

Moreover, the ontology alignment process has revealed that there are gaps in monitoring expectations between the monitor users and the chosen data, tools and theory to support them. Two groups of lacking concepts have been identified: concepts that relate to the interpretation of what value and impact current

flows and stocks have, and concepts that relate to the means and solutions that can accelerate the transition. Finally, a number of concepts have been identified as relevant to the monitoring in the CE literature but were not encountered in either of the four tested approaches. The missing concepts relate to observation quality properties, immaterial flows of assets, environmental and social impacts, legal, fiscal, and organizational contexts, and stock utility and durability.

Expressing terminology definitions as ontological rules instead of textual definitions has allowed comparing multiple definitions at the same time. Machine readable ontological rules have allowed employing automated reasoners that could process significantly more complex definitions with a large amount of classes and axioms.

Based on the lessons learned during the ontology alignment process, we recommend the following points for creating digital tools to monitor the transition towards a circular economy:

- An ontology is better suited than a relational database schema for a highly contested domain. While a relational data model represents the structure and semantic data integrity, it does not store the domain metadata which can be stored in an ontology.
- Experts and users should be involved in the ontology creation process, specifically to provide their suggestions for the correspondence between the observational and debatable properties. Monitor users, especially if they are policy makers, should be allowed to discuss and agree on which taxonomies should be used and how terms that are open to interpretation need to be defined.
- The underlying properties that led to the denotation of relevant terms should be explicitly recorded to allow monitor users to reclassify stocks and flows and realign system boundaries to produce metrics and indicators that fit their specific questions.
- If monitor users are concerned with flow and stock properties that cannot be directly found in the available data, correspondence rules need to be provided between the data properties and the denotations used by the monitor users. Given that providing such correspondence rules can be a tedious and therefore error-prone task, the rules should be published according to the FAIR³ data principles.
- Data providers should be involved in the ontology creation process to provide sufficient metadata that allows semantic matching of the entities available in the data to those asked by the monitor users.
- Fields that are available in the data but do not fit in the existing data structure of the monitoring tool, should not be discarded without discussing their relevance with the domain experts and monitor users.
- Conflicting or overlapping terms can be easier discovered if the concepts are defined as fully as possible, therefore an ontology that contains only relevant classes is not enough. The terms should be defined using sufficient object and data properties and assertions.
- An ontology needs to be reviewed every time it is being used and all newly added properties need to be critically assessed for one of the three types they belong to. The observational properties need to have their values referenced to the sources, the debatable properties need to reference chosen taxonomies and denotations and the specific properties need to reference their authors.
- Future work should explore different methods of ontology building that would include more collaborative ontology development and alignment environments.

³<https://www.go-fair.org/fair-principles/>

- New ontologies should contribute to the existing ontologies by suggesting updates, aligning new concepts and publishing the final result as an updated version.

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SUPPORTING INFORMATION

Supporting information is linked to this article on the *JIE* website:

supporting_information.pdf - additional information on the four ontology development methods and resulting definitions after the alignment

theory-centered.owl - an OWL/XML file that holds an ontology developed using a theory-centered approach

tool-centered.owl - an OWL/XML file that holds an ontology developed using a tool-centered approach

data-centered-port.owl - an OWL/XML file that holds an ontology developed using a data-centered approach based on the port dataset

data-centered-waste.owl - an OWL/XML file that holds an ontology developed using a data-centered approach based on the waste registry dataset

user-centered.owl - an OWL/XML file that holds an ontology developed using a user-centered approach based on the user interviews

circular-economy-ontology.owl - an OWL/XML file that holds an combined circular economy ontology discussed in the paper

gdse-UML.png - a UML diagram of the original GDSE database schema that has been used a basis for the tool-centered ontology

interviews.xlsx - an XLSX file that contains anonymized answers to the interview question "Welke vragen wil je beantwoord krijgen met behulp van de monitor?" (EN: "Which questions would you like to get answered with the help of the monitor"). The file contains translation of answers into English, and a list of concepts that were used for building a user-centered ontology.

ontologyalignment.csv - a CSV file that contains a list of all axioms that have been changed, removed and added to align the four ontologies into a single ontology file.

Figure Legends

Figure 1: The zoom-in on the core concepts of the merged ontology. Each concept is color-coded according to the approach it originates from.

Figure 2: The zoom-in on the observational properties of the merged ontology. Each concept is color-coded according to the approach it originates from.

Figure 3: The zoom-in on the debatable properties of the merged ontology. Each concept is color-coded according to the approach it originates from.

Figure 4: The zoom-in on the specific properties of the merged ontology. Each concept is color-coded according to the approach it originates from.