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METHODS ARTICLE

A bottom-up ontology-based approach to monitor circular economy

Aligning user expectations, tools, data and theory

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Abstract

With circular economy being high on governmental agendas, there is an increasing request from governing bodies for circularity measurements. Yet, currently existing macro-level monitoring frameworks are widely criticized for not being able to inform the decision-making. The criticism includes, among others, a lack of consensus on terminologies and definitions among scholars, politicians, and practitioners, a lack of supporting data and tools and, consequently, a lack of transparency and trustworthiness. To address those needs, a bottom-up approach to build a shared terminology is suggested as a starting point for monitoring development. The government, data providers, and tool developers are involved in the process of formal ontology development and alignment. The experiment builds upon a use case of the Amsterdam Circular Economy Monitor (2020). First, four ontology development approaches are used to create a theory-centered, a user-centered, a tool-centered, and a data-centered ontology. The ontologies are later compared, merged, and aligned to arrive at one single ontology which forms the basis of the circular economy monitor. The notes taken during the process have revealed that next to a material flow model, typical of socioeconomic metabolism analysis, policy makers are concerned with actors (i.e., institutions, companies, or groups of people) who participate in the analyzed processes and services. Furthermore, a number of terms used by the decision-makers lack clear definitions and references to be directly associated with the available data. Finally, a structured terminology alignment process between monitor users, developers, and data providers helps in exposing terminology conflicts and ambiguities.

KEYWORDS
circular economy, circular economy monitor, industrial ecology, ontology, ontology alignment, transition management

1 INTRODUCTION

The global megatrend of resource scarcity in combination with rapidly changing demographics (Retief et al., 2016) increases the pressure for the need to transition toward 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.

Yet, currently existing monitoring 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 toward a CE is supposed to achieve (Corona et al., 2019; Kirchherr et al., 2017) 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 in a specific monitoring context. 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.

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 (CEM) (mis-)align with each other. The city has a moonshot 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 toward its goals, Amsterdam is currently building a CEM which should serve as a powerful data infrastructure for CE transition monitoring and decision support. Given that a 100% material circularity is not possible from the thermodynamic perspective, to date it remains unclear what the achievable ambition is. Different sources refer to the full circularity in a range of definitions from "economy that requires no raw materials" to "waste-free economy" The ambiguity of the goal further emphasizes the lack of semantic integrity in the circular economy policy.

2 THEORY

The most prominent remark repeated in multiple reviews of macro-level monitoring frameworks 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, and local jobs) 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).

Differently from 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 semantic 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

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

		Purpose						
Publication	Domain	Waste-to-resource recommender system	Internet of Things	Product or material passport	CE business model support	Data and information exchange	Available for reuse	scale
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
Vasantha et al. (2015)	Product-service systems				+	+	No	Meso
Olivier et al. (2015)	Equipment maintenance					+	No	Meso

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.

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 & 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 (Calisto Friant et al., 2020) increases exponentially, the use of formal ontologies is rarely included into the discourse. While a SCOPUS search of the term "Circular Economy" returns 9195[1] 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 (Table 1). 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 toward a CE.

Although ontologies are often discussed in substance without explicitly stating it, out of practical reasons they are excluded from this review. An article that does not explicitly discuss an ontology would first have to go through a machine-readable ontology development process which would have to be done by the authors of this paper and would likely lead to a biased result.

It is important to notice that none of the reviewed ontologies (except for the European Waste Classification taxonomy) have been published in a machine-readable format 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.

The ontology proposed by Pauliuk et al. (2016) aims to provide a practical, mutually exclusive, and collectively exhaustive ontology that can accommodate data from any interdisciplinary model of socioeconomic metabolism (SEM) study domain. Analysis tools developed for studying the flows of SEM are able to inform CE efforts how fast material stocks grow, when and how materials become available for reuse, and how much the recovered resources are able to contribute to maintaining the necessary stocks by closing the loops. The ontology is only concerned with the physical material flow aspects of SEM studies, that is, physical material properties, locations, quantities, and processes that change them. It is a

TABLE 2 The four ontology development approaches as defined in Holsapple and Joshi (2002) used to develop an ontology for the Amsterdam CEM.

User-centered/collaborative approach	Data-centered/inductive approach
Collaborative approach focuses on eliciting domain knowledge from multiple experts that have different viewpoints toward 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-developer's 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 socioeconomic 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.

high-level ontology that aims to be as domain agnostic as possible, providing a minimal required amount of classes to support interdisciplinary research. For these reasons their ontology is more suitable to be used as a theoretical basis for this paper than the other reviewed ontologies, all of which are specific to a certain domain.

3 | METHODS AND DATA

Holsapple and Joshi (2002) have described five 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 CEM 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 repository[2]; further details about their development are available in the supporting information.

The first iteration of an Amsterdam CEM builds upon two baseline datasets that represent the major part of the linear economy: national industrial waste registry and port import/export declarations. The web application used as a basis for the CEM originates from the H2020 project REPAiR (Resource Management in Peri-Urban Areas). The Geodesign Decision Support Environment (GDSE) is a prototype web application where different stakeholders in CE strategies are able to assess their environmental and spatial impacts (Arciniegas et al., 2018; Remøy et al., 2019). The main intended users of the early stages of the Amsterdam CEM are policy and strategic advisors, and programme managers within the Municipality. More information about the CEM data, tools, and users is provided in the supporting information.

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. 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. For example, `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 the 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 their entities can be explored using the CEM tool.

The goal of the CEM is the representation of the past, current, and future material flows and stocks and their relevance to the transition toward the circular economy. Therefore the core concepts provide a minimal amount of concepts 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 core concepts of `Actor`, `Destination`, `Origin`, `InputFlow`, and `OutputFlow`. Figure 1 summarizes which classes of the combined ontology are considered the `Core Concepts`.

The most important addition is an `Actor` class, the need for which 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.

Besides the different goals to achieve and benefits to reap, different actors may have influence in the different spheres and aspects of the CE. For example, an industry player is able to invest in changing the design of its products to be easier repairable, a local government can support the repair by allocating physical space, but a consumer may still choose to throw a broken product away, even if it is cheaper and more convenient to repair it. Due to these differences, every group of actors needs specific feedback and monitoring mechanisms to understand to which extent their decisions are helping to achieve the set targets.

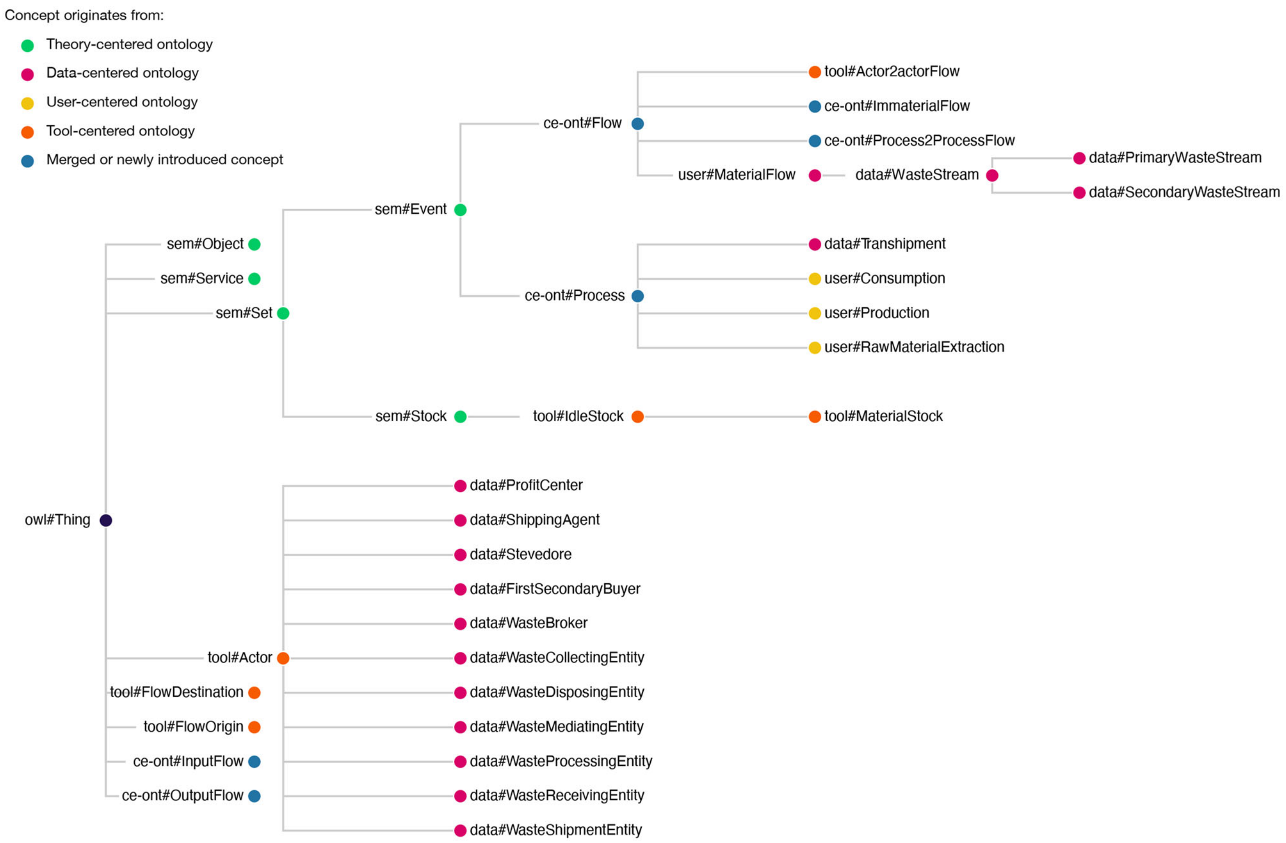

FIGURE 1 The zoom-in on the core concepts of the merged ontology. Each concept is color-coded according to the approach from which it originates.

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 and definite. Although their values may be disputable, the meaning of the properties themselves is not questionable nor ambiguous, for example, geographical locations, city, or harbor names can only refer to certain sets of values.

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 always 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 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 (Fischer-Kowalski & Weisz, 1999; Spash, 2012). When the data used to study material flows and stocks come 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 which properties of the core concepts 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 from 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

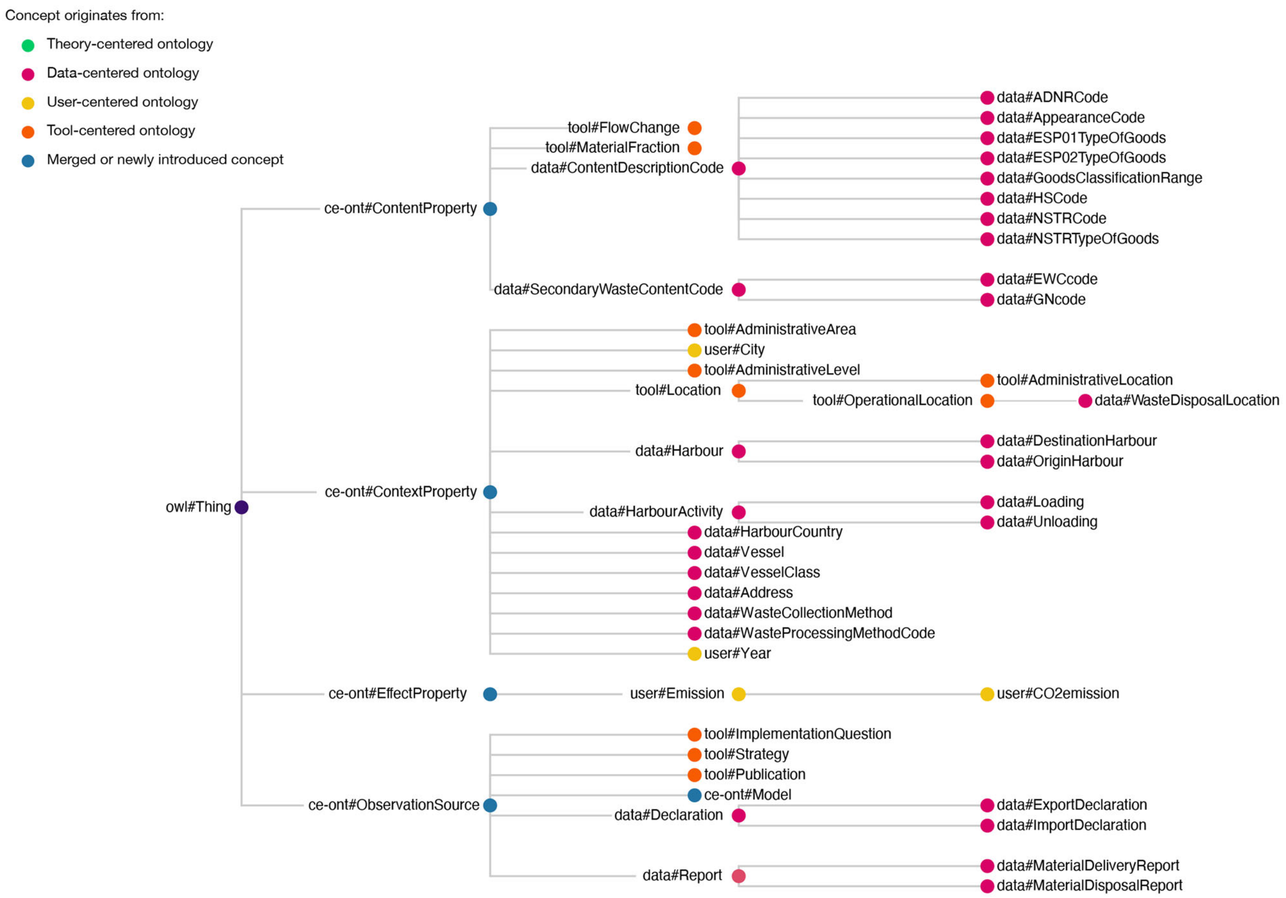

FIGURE 2 The zoom-in on the observational properties of the merged ontology. Each concept is color-coded according to the approach from which it originates.

the conversion rules are provided. For example, 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, and industrial engineering.

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. For example, `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`, and `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 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.

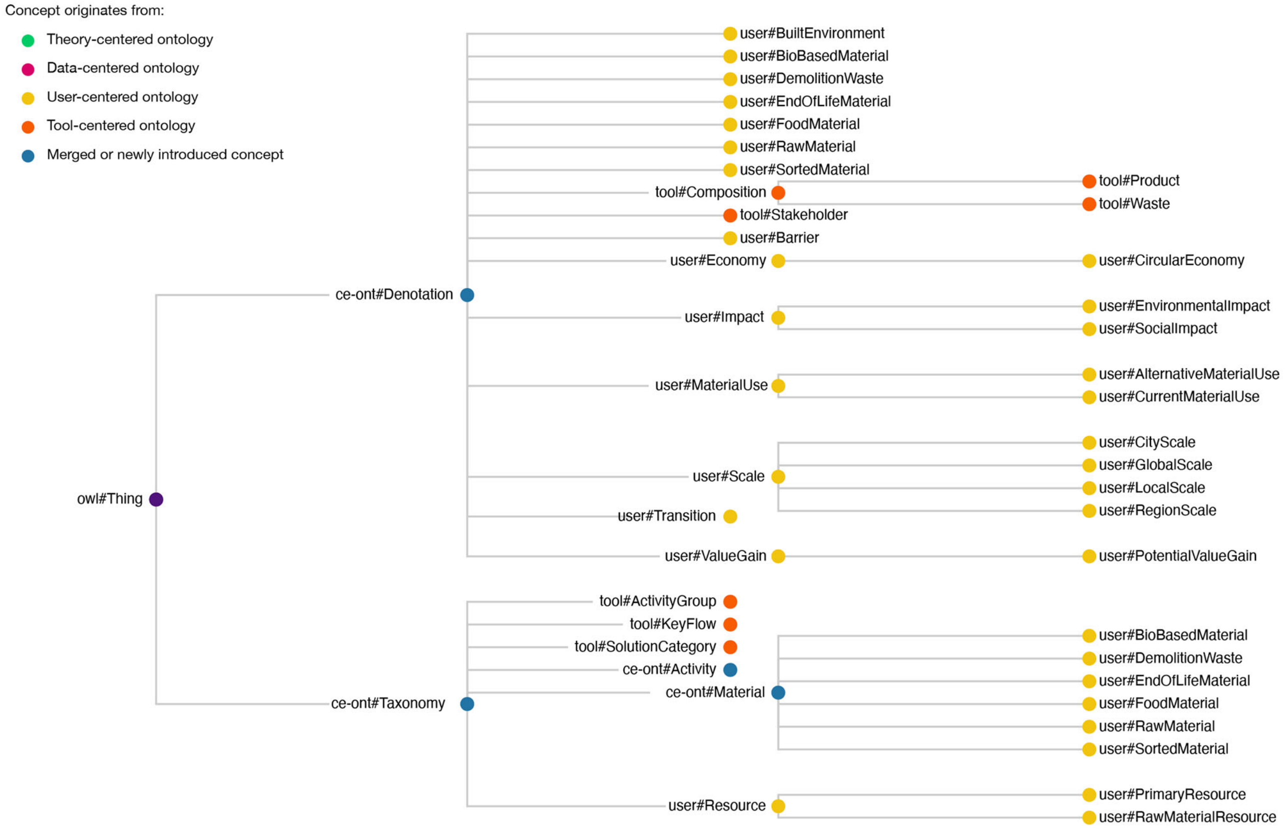

FIGURE 3 The zoom-in on the debatable properties of the merged ontology. Each concept is color-coded according to the approach from which it originates.

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, for example, 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. For example, 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 easily meet the set target.

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 are expected from the inspirational and collaborative ontology development frameworks.

5 | DISCUSSION

5.1 | Correspondence

Monitoring the transition toward 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

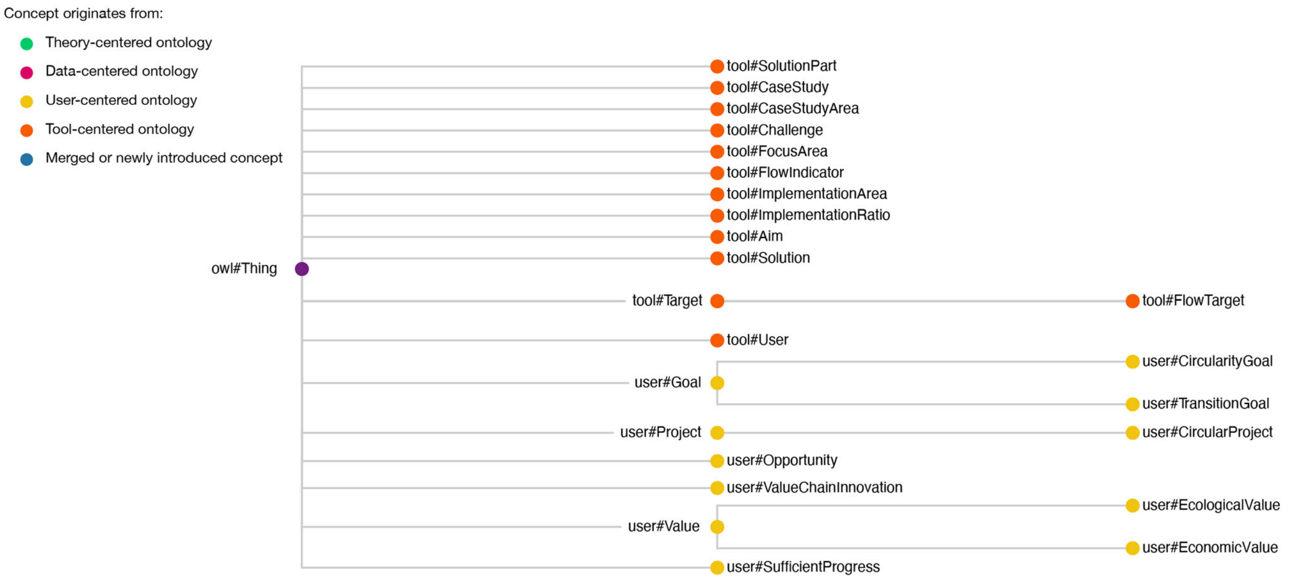

FIGURE 4 The zoom-in on the specific properties of the merged ontology. Each concept is color-coded according to the approach from which it originates.

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, and elemental composition, 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, and built environment. 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. For example, the European Waste Catalogue is made up of approximately 650 different codes, and the Harmonized System Nomenclature used in harbor declarations comprises about 5000 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, for example, 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 into 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 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.

5.4 | Missing concepts

The resulting ontology is rather an initial attempt and a representation of Amsterdam case study at a certain point in time 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 needs to be updated to meet growing user needs, increased knowledge base, tool requirements, and additional data sources.

Nevertheless, it must be noted that a number of concepts, referred to as necessary requirements for the validity of circularity metrics in the related literature, Morseletto (2020); Corona et al. (2019); Suárez-Eiroa et al. (2019); Kirchherr and van Santen (2019), have not been found in any of the four ontologies. Therefore, future work on Amsterdam CEM should include a discussion on whether excluding the following concepts out of the current monitor scope is meaningful or rather accidental and if they should be included in the upcoming CEM iterations:

- 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 toward a circular economy. The core concepts were stocks, flows, and processes—as suggested for the practical ontology for SEM by Pauliuk et al. (2016)—with actors as an additional core concept as identified in the other three approaches. Although not necessary to model physical material flows and therefore typically not mentioned in SEM studies, actors participate in processes and services. Their behavior and decisions need to be influenced to change the content and context of flows, processes, and stocks and therefore is of high relevance for policy decisions.

Although no acute terminology conflicts have been identified by aligning the four ontologies, the alignment process has been proved to be beneficial in identifying 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, for example, 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 flow of assets, environmental and social impacts, legal, fiscal, and organizational contexts, and stock utility and durability.

While the resulting integrated ontology is not yet sufficient to be used directly in a web application (CEM) due to a number of lacking definitions, it has already been used as a guidance to the policy makers for the selection of additionally needed data sources and analysis methods to fill the knowledge gaps. For example, a repeatedly expressed need for the assessment of carbon emissions resulted in conducting life cycle analysis (LCA) for the materials most commonly found in waste. This in turn caused a need for an extended ontology of waste materials to connect LCA results and waste data.

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 toward 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 FAIR[3] 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 easily 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.

- 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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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the CTO office of the Municipality of Amsterdam in the Netherlands. Restrictions apply to the availability of these data, which were used under license for this study. Data are not available from the authors and can only be accessed directly from the Municipality of Amsterdam.

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NOTE

[1] As of March 5, 2021.
[2] https://github.com/rusne/ImpactOntology/tree/master/ontologies
[3] https://www.go-fair.org/fair-principles/

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