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RESEARCH AND ANALYSIS

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A sociomaterial conceptualization of flows in industrial ecology

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Abstract

A major starting point in industrial ecology (IE) is that reaching ecological sustainability requires understanding relations between human actions and material (tangible) flows. IE studies have enabled assessments of different technical and sociotechnical configurations but only to a limited degree provided concepts that support the design of interventions for industrial ecologies. We contribute by proposing a *sociomaterial flow approach*, here applied to life cycle thinking. After problematizing some common concepts in IE, the key concepts, a procedure, and some applied variants of the proposed sociomaterial approach are presented. The approach is theoretically grounded in related sociomaterial research. This body of theories underpins our conceptualization of how flows in, for example, a product life cycle can be related to nets of human actions within one rather than several analytical frames. The sociomaterial interaction point (SMIP) is a key concept in our approach for the sociomaterial connection between material flows and actor networks. A SMIP can be described as the interactions where humans come closest to the flows. The conceptualization of the methodology provides a framework for exploring actor and action networks shaping material flows and a basis for a relational analysis of governance, organization, and management of the flows in industrial ecologies. A sociomaterial approach to flow studies can therefore help in designing more concrete sustainability interventions in industrial ecologies.

KEYWORDS
actor-network-theory, conceptualization, industrial ecology, material flows, philosophy of science, sociomaterial

1 | INTRODUCTION

A starting point in industrial ecology (IE) is that both human actions and material (tangible) flows are important to understand to achieve ecological sustainability (e.g., Boons & Howard-Grenville, 2009; Cohen-Rosenthal, 2000). White (1994, p. v) considered IE research to be about flows, environmental performance, and "influences of economic, political, regulatory and social factors on the flow, use and transformation of resources." This suggests an interest in studies that *combine social* and *material* dimensions. Our response is a sociomaterial conceptualization facilitating description and understanding of *how* the social and the material depend on each other through numerous and complex connections.

We note that others also have responded with different approaches to bringing social analysis to material flow studies. Among these, we identify broadly two approaches: "modeling" studies (cf., e.g., Deutz & Ioppolo, 2015) and "hybridization" studies (e.g., Fischer-Kowalski & Steinberger, 2011).

The "modeling" studies tend to offer versions of material flow models using particular and hypothetical social analyses as frames for modelling, for example, scenario-based LCA (e.g., Miller & Keoleian, 2015), consequential LCA (e.g., Palazzo et al., 2020), or adds some social variables to flow models, for example, agent-based modelling (e.g., Romero & Ruiz, 2014), social network analysis (e.g., Schiller et al., 2014). Although these modellings aim at supporting intervention, we identify them not to give enough attention to context and particulars for feasible problem-solving (cf., Olaya, 2012). Also, O'Rourke et al. (1996) and Vermeulen (2006) found that IE tends to rest on weak and oversimplified social ideas and that greater attention to organizational behavior and institutions is warranted.

The studies we label as "hybridized" focus on social meanings of flows and objects, as suggested by Fischer-Kowalski and Steinberger (2011). Here, we find, for example, studies of political-industrial ecology (Newell & Cousins, 2015), politics of consumption (Hultman & Corvellec, 2012), politics and spatial aspects of water flows (Saravanan et al., 2015), and the complementarity between material flow analysis (MFA) and sociotechnical studies (Wallsten, 2015). The studies offer insights into social meaning and organization around product and material flows, but give limited consideration to the influence from networks of humans on flows and environmental impact. Developing a representation of flows here could help better understand and identify opportunities for intervention toward sustainability. Covarrubias (2019) pointed more generally to complementing material-focused approaches with joint social consideration for nexus governance in urban contexts, and Niero et al. (2021) identified that actor-network-theory (ANT) through its structured coverage of both humans and material entities is useful. Moreover, model conceptualisations that capture more of the particulars of concrete situations are needed for devising sustainability strategies for real-world impacts (cf., Olaya, 2012; Wiek et al., 2012).

In this article, we present the conceptualization of a sociomaterial approach to human networks and material flows, and discuss its value for supporting change toward sustainability in relation to other IE and IE-related approaches. The methodology is *sociomaterial* in the sense of a hybrid combination of study of social and physical aspects (cf., Orlikowski, 2009).

The sociomaterial approach has been developed over 15 years through a range of activities: PhD projects, conference presentations, discussions with experts on sociomateriality, and a seminar series. The PhD projects are Brunklaus' (2008) studies on organization of and ecological impacts from housing management and Lindkvist's (2019) development and reasoning about the methodology's concepts. Seeds of these projects came from a methodological framework for environmental assessment of organizing (Baumann, 2004). Moreover, Baumann's personal communication about key concepts and building blocks for the methodology with scholars such as Bruno Latour on actor-network-theory (ANT), Richard Wilk on sociomaterial interactions, and Barbara Czarniawska on action nets has been part of the methodology development (Baumann, 2012). Concretization of the methodology took place through a seminar series in 2007–2013 and 2015–2018, with scholars in industrial ecology, organization studies, economic history, and science and technology studies.

The article covers the theoretical grounding of the proposed approach, its conceptual components, and research done for developing it. Our reasoning starts from how the study of humans and flows has been conceptualized in IE literature and shows how a sociomaterial approach extends this conceptualization (Section 2). We then show that a sociomaterial flow approach is supported by a hybrid ontology and epistemology (Sections 3 and 4). Next, we present the sociomaterial approach by outlining and explaining its concepts, a procedure, and variants of the approach (Section 5). We discuss its contribution (Section 6) before outlining our conclusions about the value of a sociomaterial approach to flows in IE and sustainability (Section 7).

2 | REASONING ABOUT TERMINOLOGY FOR MANAGEMENT OF MATERIAL FLOWS

The sociomaterial flow approach departs from a reflection about core concepts in IE: flow, stakeholder, and implementation. From this, we extended the terminology through insights from social sciences and humanities.

In technically focused IE studies, a *flow* has generally denoted physical aspects of transfers within and between technical processes (e.g., Clift & Druckman, 2016). Life cycle assessment (LCA) (e.g., Hauschild et al., 2018) and material flow analysis (MFA) (Brunner & Rechberger, 2017) describe the material connections between technical processes but leave out how humans set flows in motion and determine their shape. In studies focused on actor-modeling (e.g., agent-based modeling), industrial flows are primarily seen as affected by the human and social factors that become specified as parameters in the models (cf., Romero & Ruiz, 2014). The actor-modeling studies focus on searching for an optimal combination of actors and flows. A complement can be to explain how networks of humans can be created and upheld, why actors often do not act as stipulated, why the material properties of a flow may limit the possibilities to modify it, and the need for human activity, which may act via computers, to keep the flows flowing.

A sociomaterial take on the flow concept recognizes *actors* (Latour, 2004)—individual persons and constellations of them—as *enablers and in other ways determinants of the flows* (Baumann, 2012) when the flows in question are, for example, industrial flows. This allows for explicit description and analysis of interests, organization and management of flows.

Instead, in IE, the concept *stakeholder* is often used to signify people related to a material flow in an imprecise way. According to stakeholder theory, managers need to consider other groups than shareholders for the success of a firm (Freeman et al., 2004). In life cycle management, where the term stakeholder is prominently used (cf., Sonnemann & Margni, 2015), there is limited attention to what stake stakeholders have and in what.

TABLE 1 An extended terminology for studies of material flows and humans

Currently prominent terms	Additional concepts
Flow	Actor (any actor); as *enabler and in other ways determinant of the flow*
Stakeholder (primarily relationships that companies want to manage)	For relationships: role; agency; practice; organize; network For types of events: action; perception; interpretation For determining how change occurs: structure; process
Implementation	Adoption; translation

In modeling studies in IE (e.g., scenario-based LCA) humans have primarily been modelled as behaviors directly influencing material flows (such as finding a product affordable) (cf., e.g., Miller & Keoleian, 2015). Framing people as actors, stakeholders or behavior matters; actors have agency, while stakeholders are analyzed so that managers can take appropriate action and behaviors are responses to external stimuli.

We searched the social sciences for concepts on connections between actions and actors, focusing on generic connection types rather than reasons such as politics and religion. Activities can be understood through *roles* (Vermeulen, 2006), *agency* (Robichaud & Cooren, 2013) of actors, or *practices* (Shove et al., 2012). How actors are *organized* (Czarniawska, 2008) and their participation in *networks* (Latour, 2005) can also describe relations. Relations, in turn, depend on events that can be studied by considering each specific *action* (Czarniawska, 2008), and through the concepts *perception* (Vermeulen, 2006) and *interpretation* (Hatch, 2006). Determinants of change can also be studied via *structure* (Mol & Spaargaren, 2005) and *process* (Vermeulen, 2006). These concepts provide lenses for considering when an actor is relevant for a flow.

Implementation is a common concept for change in IE literature (cf., Deutz & Ioppolo, 2015). Since implementation typically represents a top-down approach, we find it useful to consider other change conceptualizations. One is *adoption* (Vermeulen, 2006) in the sense of beginning to follow or use an approach. Another is *translation* (Latour, 2005)—focusing on disagreements that lead to an outcome through a negotiation process.

Table 1 summarizes conventional IE terminology and the additional terminology we find useful for approaching IE flows and networks in a socio-material way.

3 | AN ONTOLOGICAL AND EPISTEMOLOGICAL RESEARCH GAP

We believe that an approach that combines social aspects, including meaning, and material aspects ought to be analytically coherent. Such an approach needs foundation in a common language for meaning and the material, while acknowledging that meaning has characteristics not captured by a material perspective. We present a hybrid ontology and epistemology that can provide coherence.

Approaches to human actions and material aspects vary across disciplines. IE, according to Allenby (2006), combines the scientific aim of mapping reality with the technological task to change it. The scientific and technological focuses are compatible when knowledge is treated as objective (Allenby, 2006). This ontological and epistemological choice for compatibility may have resulted in IE focusing more on generic and macroscopic aspects and less on case-specific particulars (cf., Olaya, 2012)—another choice is possible. Philosophy of social science (Braybrooke, 2005) provides three overarching academic perspectives that can be used for comparing the dominant knowledge perspective in IE with those in other disciplines:

- Naturalistic. An objective ontology and epistemology have been provided from the natural sciences and suggests searching for independent causal patterns. We find the naturalistic approach in fundamental, and often implicit, IE assumptions.
- Interpretative. In this approach, "researchers seek to interpret fully the meaning of people's actions, including their efforts to communicate and cooperate" (Braybrooke, 2005, p. 964). Description of social rules is the closest this school comes to causal explanations.
- Critical. Causes have partly been brought back into study by critical scholars. They have questioned conventional interpretations because they may result in overshadowing social inequalities.

We find that the contributions from each of the three philosophical schools can be acknowledged in a hybrid but analytically coherent approach where actors, technologies, and material flows and their modeled representations are understood in a "realist" constructivist way with both human and nonhuman actors, which is different from social constructivism (Latour, 2005; Justesen, 2020).

4 | SOCIOMATERIAL CONSTRUCTIVISM

The sociomaterial approach for IE is based on the related works, by three scholars, on symmetric sociomateriality: Latour's (2005) *actor-network-theory* (ANT) in science and technology studies, Barad's (2003) theorizing on *agential realism* in philosophy, and Harman's (2011) proposed *object-oriented ontology* (OOO) in philosophy (Harman, 2011). OOO, agential realism, and ANT share the notion that humans and nonhumans, or social and material aspects, are equally relevant for explaining phenomena. Latour's (2005) ANT explicitly uses the term symmetry to denote this equality of importance. We explain the relevance of their research for IE by first outlining a larger body of literature on combining social and material aspects as relevant for society, and by then showing particular aspects of hybridity.

The three scholars' research is part of studies on physical objects from perspectives in social sciences and humanities. Each of the labels "posthumanist" studies (Bijker & Pinch, 2012), "new materialism" (Lemke, 2014), "material turn" (Bennett & Joyce, 2010), and "ontological turn" (Escobar, 2007) cover all or large parts of this diverse body of research. The research emphasizes, for example, the exploration of how material objects in the arts and everyday life play unexpected roles (Brown, 2004), the thorough consideration of the properties of man-made items when interacting with them (Henare et al., 2007), and research on how humans sense and react emotionally and aesthetically to physical objects in museums (Dudley, 2010). According to Latour (2005), a material dimension of society complements the "oversocialized" studies in the social sciences that underestimate the effect of interactions between material objects and humans. Materialistic posthumanist studies inspire the consideration of different relations between material flows and human actions and show that sociomaterial approaches are widely applicable.

Within posthumanism, Latour (2005) has developed the *ANT* method for understanding how material objects constrain interaction in networks of humans, and how humans need these objects in trying to reach objectives. ANT's consideration is, to use Latour's (2005) term, *constructivist*. In this constructivist view, considering material and social entities separately does not make sense; this constitutes a flat ontology (Latour, 1996). Latour uses the term actant to capture influence not necessarily driven by conscious intention (Czarniawska, 2017). Regarding procedure, a typical ANT study is as follows: "After having located the phenomenon to study, [the study] begins with a preliminary identification of actants: beings or things that act and are acted upon. It continues by tracing connections between observed programs and anti-programs of action, until it is clear *how* some actants became actors or even macro actors, elucidating the process of building a network" (Czarniawska, 2017, p. 161, original emphasis). ANT is analytically flexible, thus enabling a more open approach than a (predefined) focus on the action groups at the core of practice theories (cf., Spaargaren et al., 2016). Translated to the IE context, ANT suggests that material flows and humans interact and influence each other and do not always perform as intended.

Barad (2007) has presented an *agential realism* that primarily, like ANT, considers a constructivist sociomateriality, while providing additional reasoning about a selective process of constructing human meaning. For IE, such selectivity could highlight that terminology for material flows and human action assists in isolating them from other entities, when the terminology only provides limited understanding of relationships between entities.

Furthering constructivist sociomateriality, Harman's (2011) *OOO* is an ontology also considering that any entity, including a person, can be partially isolated. He has shown that usually only a small portion of an object's properties influences another object. In relation to IE, OOO suggests that a person might have considerably less influence on a material flow than expected.

Applying a constructivist epistemological perspective and a symmetrical ontology to IE produces a theoretically grounded conceptualization of the human-material interactions that create and shape material flows and of human networks surrounding and connecting them, enabling a linkage between material flows and the social realm. Such human-material links are central to the presented sociomaterial flow approach.

5 | A SOCIOMATERIAL APPROACH FOR IDENTIFYING RELATIONS BETWEEN NETWORKS OF HUMANS AND ECOLOGICAL IMPACTS

In this section, we outline the sociomaterial approach for identification and description of relations between networks of humans and ecological impacts via technology and material flows. Our aim is an IE approach that assists identifying possibilities for intervention, thus supporting change. For this, conceptualizations and models that capture more of the particulars of concrete situations is thought to aid sustainability interventions in industrial ecologies (cf., Olaya, 2012; Wiek et al., 2012). Our approach is designed both for documenting implicit actors in flow models, and for revealing nonintuitive connections. The approach is based on the presented extended terminology for flows and humans, on the presented constructivist sociomaterialism, and on explorative case studies (cf., Baumann et al., 2015). From the case studies, we found it useful to outline concepts (Sections 5.1 and 5.2) and a procedure (Section 5.3). We exemplify the approach trough a simplified case on bread and bakery planning (Lindkvist, 2018) and residential property management (Brunklaus, 2009) (Section 5.4). Finally, we present three ways of scoping life cycle studies sociomaterially (Section 5.5).

5.1 | Core concepts

The proposed approach is based on a sociomaterial conceptualization of case-specific and detailed complexities of flows and networks of humans. Simply put, the approach combines two types of study. We call the first type a *material flow study*. This has been tested as a constructivist use of life cycle assessment (LCA). Other options include a corresponding constructivist use of material flow analysis (MFA) because of similarities between

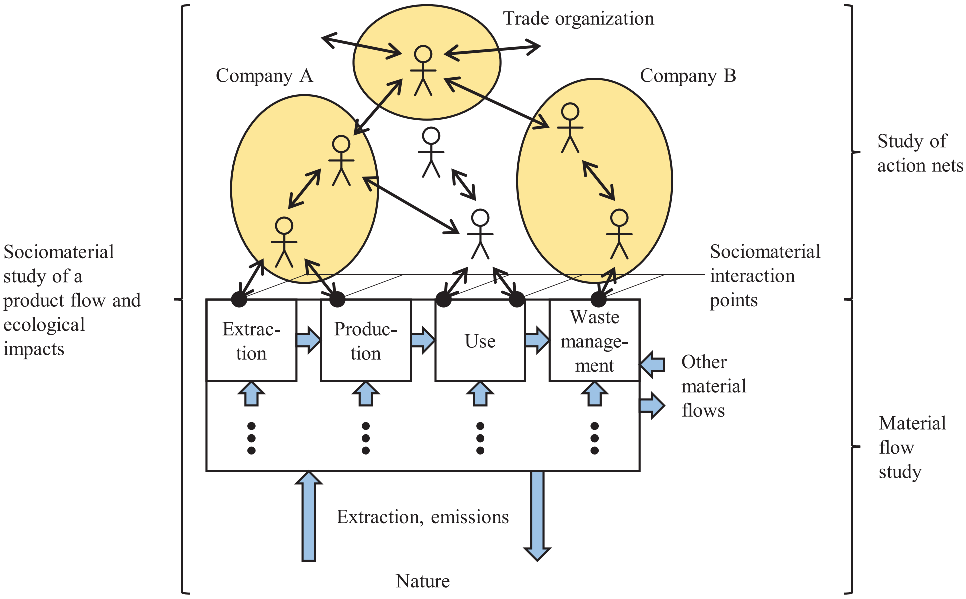

FIGURE 1 The sociomaterial model of flows and humans central to the proposed approach. A hypothetical product flow illustrates the model. In the model, boxes represent technical processes, thick arrows represent material flows, vertically consecutive dots represent relations via further material flows, and thin arrows represent human interactions. *Source*: The figure is adapted from an article (https://doi.org/10.3390/recycling2040023) created by Mathias Lindkvist and Henrikke Baumann, Licensed by MDPI, Basel, Switzerland under CC BY 4.0 (http://creativecommons.org/licenses/by/4.0/), and Copyrighted in 2017 by the Authors

flows covered in LCA and MFA (cf., Deutz & Ioppolo, 2015). The second type is a constructivist organizational *study of action nets* (Czarniawska, 2004). *Socio-material interaction points* (SMIPs) (Baumann, 2008) link the two types of study. Different SMIPs along a flow are socially connected via *action nets*. Figure 1 illustrates these flows, SMIPs, and nets.

The "flows" that humans create, including anthropogenic flows in nature, are in the sociomaterial approach conceptualized as *man-made flows*—where "man-made" refers to occurring because of human involvement rather than spontaneously (Oxford, 2020). The term man-made flow relates to large parts of the material flows in LCA and MFA.

SMIPs conceptualize human actions closest to man-made flows. Example SMIPs are when humans lift, watch, and push material objects in or directly controlling (e.g., via computers) a flow. These interactions are important, because decision-makers may not on beforehand know which SMIPs they need to influence via chains of actors in order to achieve a certain ecological objective. The bread case study showed that good knowledge of customer demand can facilitate avoiding overproduction and related ecological impacts unless a chain of actors makes it difficult to receive sufficient information on the actual demand at the SMIPs where this demand occurs. A chain of actions connecting a SMIP to a decision may even involve several different organizations. The abbreviation SMIP is short for *sociomaterial interaction point*. The use of the term "sociomaterial" is inspired by environmental sociology studies on knowledge and practices related to energy use (Guy & Shove, 2000) and environmental anthropology (R. Wilk, personal communication, December 2007). "Interactions" refer to the direction of influence possibly going either way. Regarding the bread case, whether a slice of bread is eaten or not can depend on a combination of how hungry a person is and bread quality. The term "point" highlights that humans can interact with a man-made flow at more than one SMIP along a flow.

SMIPs, in turn, are connected through *action nets* (e.g., Czarniawska, 2004)—nets of interactions between humans. These nets conceptualize actions influencing each other and that are typically connected via several or many humans and material entities, within organizations and in nets spanning several organizations (e.g., companies and environmental nongovernmental organizations (NGOs)). Regarding the bread case, coordinating demand monitoring and adjustment of production size occurred through an action net involving several persons in different locations and roles—this net determined whether overproduction and associated ecological impacts could be avoided. An action net is considered to result from rather than cause interactions involving humans and material objects, and, therefore, "net" is preferred over "organization." How to study organizational processes is not stipulated by the action nets concept. Consequently, the concept facilitates exploration for further understanding the many different types of material flows and how they are organized. Regarding which actions to include, advice from the research behind the action-net concept suggests including actions clearly relevant to the studied phenomenon (cf., Czarniawska, 2004). In the proposed approach, the net, therefore, consists of actions clearly linked to the studied man-made flow. If a flow is found to depend considerably on, for example, activities in global finance, it might suit to study that phenomenon in relation to the flow (cf., Magnolo, 2019).

5.2 | Supporting conceptualizations for sociomaterial identification and description

We found two additional notions useful when analyzing the organization of man-made flows: *incompatibility between alternatives* and *limited connection* (between different actors and other objects).

The *limited connections* concept originates in Harman's (2011) OOO and denotes that action nets typically contain lacking, infrequent, and malfunctioning links between actors and between actors and man-made flows. Considering limited connections could help not underestimating sustainability challenges.

The *incompatibility between alternatives* notion originates in Barad's (2003) agential realism and points out potential incompatibilities between different practiced and suggested ways of handling different ecological and other challenges. In the bread case, the provision of a broad variety of products can be incompatible with being able to in-house monitor fluctuations in the price of ingredients and, therefore, may require using nationwide purchasing organizations rather than local suppliers, with associated ecological consequences from transports.

5.3 | Procedure

When performing a study with the proposed sociomaterial flow approach, we arrived at the following working sequence of five steps. The procedure is developed from a number of test studies (cf., Lindkvist, 2018).

1. Describe the man-made flows and the, from them, resulting ecological impacts.
2. Identify the sociomaterial interaction points (SMIPs).
3. Trace and describe action nets between the SMIPs.
4. Compose an overview—by merging the descriptions from Steps 1–3.
5. Analyze how actions in the action nets affect ecological impacts.

Step 1 can consist of a constructivist use of a quantitative LCA study. This acknowledges that LCA results are based on reality but that humans select which aspects of this reality to analyze. Different sizes of man-made flows can be covered. The approach has been tested on product life cycles of, for example, individual bakeries (Lindkvist, 2018), nationwide packaging (Lindkvist & Baumann, 2017), and global flows for rare earth elements of batteries and magnets for electric vehicles (Eriksson & Olsson, 2011). Step 2 identifies human interactions at the man-made flow. The step can be informed by Step 1 and by qualitative document studies, interviews, and observation (cf., e.g., Silverman, 2006). We have found it useful to interview a person with both an overview of a range of activities in an organization and knowledge of SMIPs. Step 3 typically consists of a qualitative organizational study based on documents, interviews, and observation (cf., e.g., Silverman, 2006). Steps 4 and 5 synthesize the findings from Steps 1–3.

We have used discourse and conversation analysis as interpretation filters for the organizational study. Studies applying discourse analysis consider all text and talk as performative actions (Silverman, 2006). Additional limitations in conversation sequences are made available through conversation analysis (Silverman, 2006). Discourse analysis and conversation analysis align with critical management studies (e.g., Hatch, 2006).

5.4 | Example cases: Bread and residential housing

We present here applications of the sociomaterial approach to a case study on bakeries and bread by Lindkvist (2018) and another on housing management by Brunklaus (2009).

The bread study considers the organization of bread production and consumption. Although the bread life cycle was considered as a whole, the focus of the organizational study was on the interactions between humans and material flows in and around the bakeries, as these are nodes of ecologically important flows (e.g., mixing of different ingredients for different products). Three Swedish bakeries and their bread product life cycles were compared. The bakeries were located in the major cities Gothenburg and Malmö in south western Sweden. Data sources were literature, including LCA publications, websites of the three bakeries, and combined interviews and observation at each bakery with a member of staff with insight into both production practices and the organization.

The study identified seven findings on organizational influence on environmental performance, regarding supply, production, distribution, and retail. We here exemplify this through one of these findings—on discarding of bread. Discarding of unsold bread, and the associated additional ecological impacts, had reached very high levels at one bakery's retailers. The discarding was found to depend on a number of factors: the fluctuations of customer demand had increased, customers required a broad range of fresh bread products to be available throughout the opening hours, the number of retailers had increased, the administrative resources for monitoring demand had not changed, and information on demand passed through

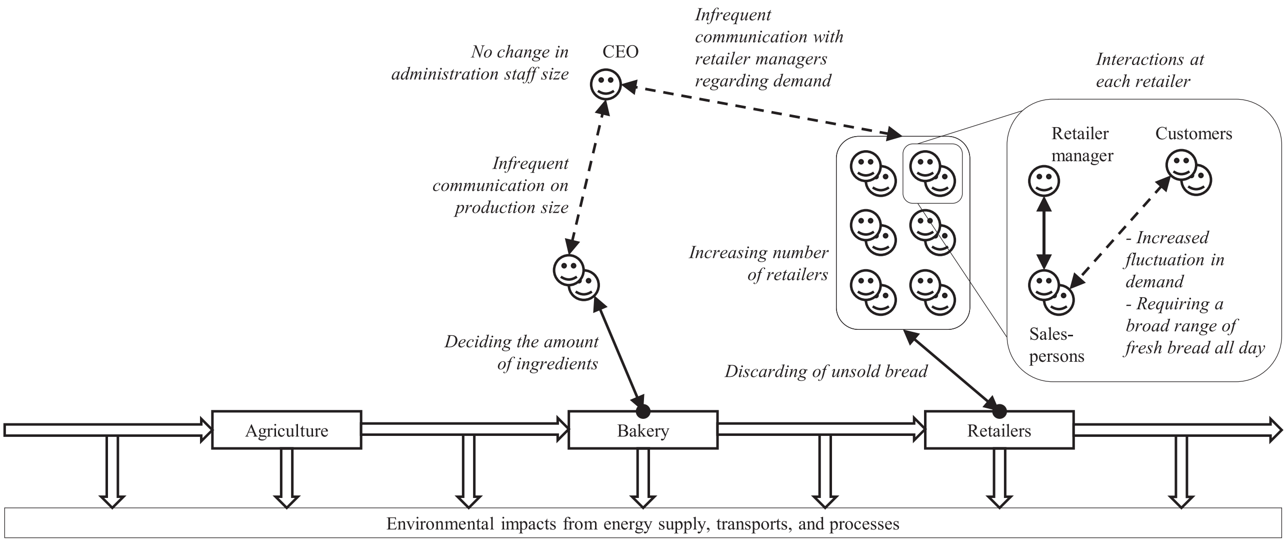

FIGURE 2 Illustration of environmentally relevant and nonintuitive action nets identified by applying the sociomaterial approach. For a case of high levels of discarding at a bakery in Sweden. The figure in particular focuses on illustrating how interactions between sociomaterial interaction points, here shown as dots, can pass several and in some cases only infrequently interacting persons. Solid double-edged arrows represent frequent interaction. Dashed double-edged arrows represent infrequent interaction. Based on descriptions by Lindkvist (2018)

several actors before reaching the persons who decided on the size of production. The consideration of SMIPs and action nets between bread production and sales enabled the identification of these organization and management matters and that they mattered more for waste production than technology here. Figure 2 illustrates the findings.

In the second case, residential property management organizations in Gothenburg, Sweden were analyzed for the influence of operations and maintenance organization on environmental performance. In order to capture the environmental influence from different ways of organizing operations and maintenance, architecturally and technically very similar buildings close to each other were studied. Interactions between humans and material flows were mainly studied in operation and maintenance of the buildings, because these form nodes where several material flows meet and environmentally important handling of them occurs. The study focused on energy and water use because they constituted a major share of the environmental life cycle impacts. Data sources include around 20 interviews, 20 days of observation, and 200 documents covering a range of aspects, including actual operational practices and management strategies.

We illustrate the study's findings through results on energy use. Results showed that a property management approach where a single caretaker calibrated the different technical systems and where renovation was adjusted to both ecological and cultural heritage concerns led to several changes to less energy intense infrastructure in one of the organizations. This was contrasted by the other organization, where several specialists took care of different parts of the technical systems in the building and with limited coordination, were responsible for a large number of properties, and operated mainly when an emergency occurred, and where renovation was focused on "raising the standard" (e.g., making the bathrooms appear more neat) of the building with less priority to environmental measures. The different strategies were found to explain up to 30% lower energy use in the first case despite, in all other aspects, very similar buildings.

5.5 | Tested organizational scopes with the sociomaterial approach

In the development of the approach, different organizational scopes were tested, as illustrated in Figure 3. Each of these covers how action nets via SMIPs determine the environmental performance of material flows, but differs with regard to the level of detail the action net and material flows are explored and the extent of the flow for which its organizing is studied in detail.

One scope centers the action net study on a life cycle node where ecologically important man-made flows meet and the organizational processes around it: *life cycle nodal organization* (LCNO) studies. The case studies on bread (Lindkvist, 2018) and housing management (Brunklaus, 2009) utilize this scope.

A study on passive housing (Brunklaus et al., 2010) was used to develop *actor-LCA*. The scope is based on an LCA study, but focusses on how the environmental impacts are connected to the different actors along the life cycle instead of the different technical processes in this life cycle. An actor-LCA shows the distribution of environmental impacts per actor. When an actor makes a choice affecting the overall environmental impact of the life cycle, the distribution of impact changes across the actors in the chain. This has implications for distribution of environmental responsibility in the chain.

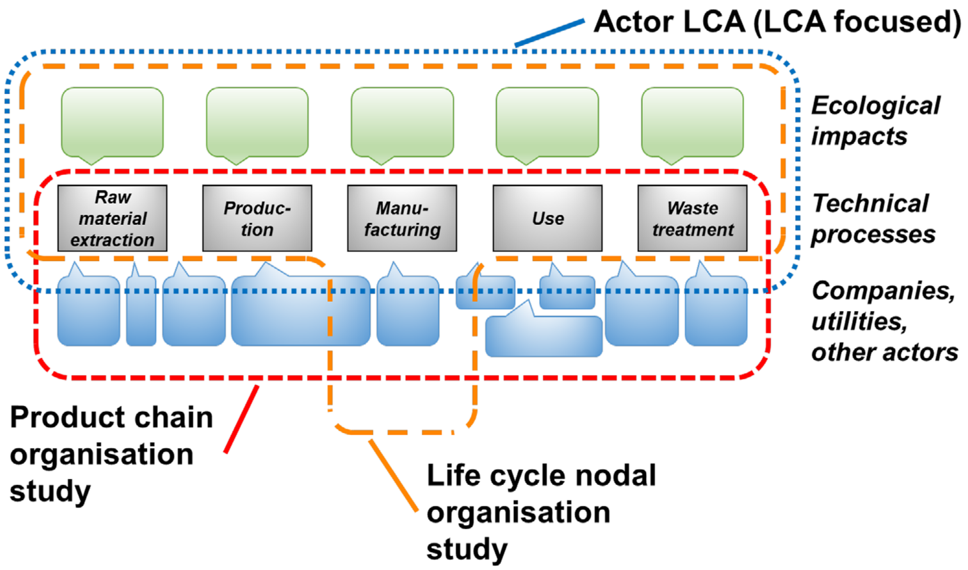

FIGURE 3 Tested organizational scopes of the sociomaterial flow approach for industrial ecologies. Abbreviations: LCA, life cycle assessment
Source: The figure is adapted from a PhD dissertation by Lindkvist (2019), and the authors of this article have permission to use the figure

Organizational structures and processes are in focus in the *product chain organization* (PCO) scope. PCO studies consider action nets along whole product life cycles. PCO case studies have been performed on, among else, cocoa (Afrane et al., 2013), diapers (Gullbring et al., 2010), and packaging (Lindkvist & Baumann, 2017).

The choice of scope influences the types of findings from socio-material flow studies. We exemplify this by relating LCNO studies on residential housing management (Brunklaus, 2009) and the organization of bakeries, bowling halls, cement plants, coach operators, and road management (Lindkvist, 2018), to PCO studies on supply chain certification (Afrane et al., 2013) and the governance and management of global material flows for batteries and magnets (Eriksson & Olsson, 2011). The LCNO studies showed that different ways of organizing a company or site can result in different levels of life cycle ecological impacts. The PCO studies enabled identification of conflicts of interest among the actors (Afrane et al., 2013) and institutional "bottlenecks" (Eriksson & Olsson, 2011). The studies using the socio-material methodology have identified the importance of actors and their organizing for life cycle environmental performance—these actors are at best implicit in LCA studies, thereby limiting analysis for effective LCM.

6 | DISCUSSION

This section discusses our sociomaterial approach in relation to LCA, other constructivist sociomaterial conceptualizations, macroscopic frameworks, and studies on priorities for sustainability transitions.

6.1 | Life cycle assessment

The sociomaterial approach has mainly been developed by complementing the environmental analysis of flows in product-LCA (e.g., Baumann & Tillman, 2004) with additional information about actors and networks, and by reframing this hybridized study through a sociomaterial lens. While conventional LCA aims for scientific rigor (cf., Bjørn et al., 2018) and support rational decision-making between clear alternatives, life cycle study with a sociomaterial approach is designed for enabling organizational learning and thereby change (cf., Baumann, 1998).

With a sociomaterial approach, also management aspects can be considered, thereby providing models that capture more of the particulars of concrete situations and are better suited as basis for sustainability interventions (cf., Olaya, 2012; González-Márquez & Toledo, 2020). In relation to a conventional LCA, a sociomaterial life cycle study enables comparisons between current product life cycles and their organization and likely future ones. In the bread case, using the sociomaterial approach highlighted that environmental performance depends on the coordination of a range of activities; this would have been difficult to identify with an LCA.

6.2 | Hybrid approaches

Other hybrid and IE-related approaches have identified sustainability-relevant interactions between the social and the material. Hultman and Corvellec (2012) showed that waste management policies can both promote recycling and lead to rebound effects. Newell and Cousins' (2015) political-industrial ecology can highlight that contributions to environmental impacts can vary among persons along a material flow. Saravanan et al. (2015) illustrated how geographical differences in water networks density led to water flow infrastructure in a city being coupled with political issues of water-based disease. Wallsten (2015) suggested the use of social constructivist studies next to an MFA without integrating the types of study.

These hybrid IE-related studies point out potentially unexpected and contrasting aspects connected to man-made flows but do not provide any methodology. One example is rebound effects (Hultman & Corvellec, 2012), through which a reduction of the discarding in our bread case could lead to decreased bread prices and subsequent increased purchasing of other ecologically impacting products, and through which similar effects could result from energy efficiency in housing management. Our approach could contribute by describing how any change, including trying to avoid rebound effects, of the environmental performance of a man-made flow can depend on understanding complex and nonintuitive case-specific relations between SMIPs. Regarding the hybrid research by Newell and Cousins (2015) and Saravanan et al. (2015), they have made actor-flow studies similar to ours, but have not provided a conceptualized methodology. Wallsten (2015) advised against integrating social and material approaches for practical research reasons, but our research shows that it can be feasible and fruitful. Summarizing, others have followed hybrid approaches; we provide a coherent methodological framework that together with the identified analyses in the other hybrid IE-related studies could result in interesting studies in the future.

6.3 | Macroscopic frameworks

Within IE, there are what we here call macroscopic frameworks that provide worldviews of society-nature relations. One is Fischer-Kowalski and Weisz' (1999) conceptual model with two different but interacting spheres: a material and a symbolic sphere. The approach is abstract and is therefore not applied to practical situations. Also, the two spheres do not appear to have a common ontological and epistemological base, which has been the focus in our efforts behind the sociomaterial approach. Another is Pauliuk and Hertwich' (2015) framework that consists of seven compartments of reality on a scale from purely natural to social. The sociomaterial approach, in contrast, operates with connections (Latour, 1996), rather than with separate compartments. A third framework is McGinnis and Ostrom's (2014) categorizing of nature-society relations via five distinct systems of, among other, resource units and actors. Again, contrary to sociomateriality, their framework compartmentalizes reality.

6.4 | Priorities for sustainability transitions

Different researchers prioritize their efforts toward sustainability differently. In a welcome attention to human agency, Otto et al. (2019) tries to bring that into theoretical world-earth system models, identifying how the richest fraction of humans with the proportionally largest shares of ecological impacts also have largest opportunities to change and influence others. This leads to an argument for prioritizing sustainability efforts that target the richest rather than the poorest. Although this is a compelling general argument, it is not clear what practical actions can bring about such change. Others suggest examining the politics of production and consumption (Newell & Cousins, 2015) and what business models can do for sustainability (Boons & Lüdeke-Freund, 2013).

Where others construct universalist theories or conduct problem-focused research, we have constructed a methodological approach in the vein of relational and solutions-oriented sustainability research (cf., Wiek et al., 2012). The possibility to capture particulars in concrete situations makes the sociomaterial approach applicable for problem-solving. It is aligned with lessons from organization research and from transition studies that point to the practical challenge to "involve millions of citizens who need to modify their purchase decisions, user practices, beliefs, cultural conventions and skills" (Geels et al., 2017, p 1243) and the need to support business because of their capabilities for making sustainability transitions happen (Geels et al., 2017).

Our sociomaterial approach can appear somewhat limited to the micro-level, such as in the bread case (Lindkvist, 2018), and thereby not address the large sustainability challenges. The approach has, however, as mentioned been tested for different geographical scales, including a national level (Lindkvist & Baumann, 2017) and globally (Eriksson & Olsson, 2011). The sociomaterial approach allows for the identification of where certain actors, for example, in product chains wield influence over others, determining institutional arrangements (cf., Afrane et al., 2013; Chakraborty et al., 2020). This identification can support effective problem solving.

7 | CONCLUSION

The presented sociomaterial flow approach aims to capture new aspects of industrial ecologies. It adds information about particulars regarding actors and action-nets to more conventional modeling of man-made material flows and their resulting ecological impacts. The approach is constructivist, enabling interpretive and critical analysis toward designing interventions and problem-solving considering both technical and social organizational aspects. This is a contribution to Industrial Ecology methods where flow studies have had either a technical focus or a social framing. The sociomaterial approach can also be a structured complement to approaches on the social *meaning* of the flows.

The related work of three scholars provided foundational input to the symmetric and flat sociomaterial conceptualization at the core of the approach. Therefore, the approach can coherently take a constructivist perspective on material flow study and combine it with the study of action nets. SMIPs, that is, sociomaterial interaction points, conceptualize the sociomateriality of the meeting between social and material.

We discussed the contribution of our approach relative the findings of our case studies, similar approaches, and sustainability research aims. The approach can be effective for designing interventions that address sustainability problems more comprehensively (cf., Olaya, 2012; Geels et al., 2017). It might also encourage more scholars from the social sciences to interact with Industrial Ecology.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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