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RESEARCH

Inside the Rhizome[1] of a Territorial Circular Ecosystem. How to Cope With Networking Relations Between Actors of Sustainable Development Practices?

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Abstract
The circular economy (CE) has gained increasing prominence in academic research and policy design initiated by public authorities and institutions. In response to the limitations of linear economies and their ecological and environmental impacts, this approach proposes an alternative model that seeks to reconcile economic performance with ecological balance. The implementation of CE practices necessitates both a systemic and territorially rooted approach, where spatial proximity between resources and the various stages of production or recycling is important, as is the organisation of actors, infrastructures, and institutions capable of generating interdependencies, positive externalities, and shared trajectories. To address this need, we propose to study the notion of Territorial Circular Ecosystem (TCE), which integrates economic, environmental, spatial, and institutional components into a coherent logic grounded in place-based governance, and to examine its main characteristics. In particular, we highlight the different components of a TCE, the various actors and their interactions, and then demonstrate, through a case study, how it is possible to analyse and characterise the internal links, structure, and spatial relations. Methodologically, we rely on approaches to social network analysis and proximity relationships to achieve this.

1 Introduction

The circular economy (CE) has increasingly gained prominence in academic research and policy design initiated by public authorities and institutions (Hachaichi and Bourdin 2023). Faced with accelerating environmental degradation, the depletion

[1]The term "rhizome" refers to the approach developed by Deleuze and Guattari (1987), which describes a structure that evolves constantly in all horizontal directions, devoid of levels, and opposed to any notion of a pyramidal hierarchy, where each element can influence any other.

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of natural resources, and the collapse of biodiversity, CE offers an alternative model that seeks to reconcile economic performance with ecological balance. This approach moves away from the conventional linear model of production, which has long relied on the extraction, transformation, and disposal of raw materials, often resulting in significant losses at each stage. In contrast, CE promotes a more rational and integrated use of natural resources. It adheres to the 3R framework — Reduce, Reuse, Recycle — or even to the more ambitious 10 R strategy - Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover (Kirchherr et al. 2017) - as a guiding principle for minimising environmental externalities while preserving material utility throughout extended life cycles (Ghisellini et al. 2016; Geissdoerfer et al. 2017).

Initially rooted in environmental engineering and industrial ecology (Frosch and Gallopoulos 1989; Ayres and Ayres 2002), CE has gradually evolved into a multifaceted concept that now encompasses technical operations, institutional settings, social behaviours, and economic coordination mechanisms (Korhonen et al., 2018). Therefore, it must necessarily be based on a strong systemic dimension. The effective implementation of CE principles cannot rely on isolated or fragmented actions. Instead, it demands a systemic configuration of actors, skills, infrastructures, and institutions capable of generating interdependencies, positive externalities, and shared trajectories, positioning them as components of a larger system. A single firm acting alone has limited capacity to create transformative change. What truly matters is the overall system of interactions, which can generate complementarities, resource optimisation, and collective benefits that far exceed those of standalone initiatives (Murray et al. 2017; Blomsma and Brennan 2017).

This systemic logic necessitates a territorial embeddedness of circular practices. Spatial proximity plays a critical role in enabling the coordination of flows, actors, and infrastructures. Circularity loses part of its environmental benefits when resources, waste, or intermediate products must travel over long distances through fragmented global value chains. Territorial anchoring provides a more coherent and efficient setting, where local stakeholders can co-develop repair, reuse, and recycling strategies and foster industrial symbiosis and resource sharing (Chertow 2000; Paquin and Howard-Grenville 2012). In many cases, these territorial configurations also support job creation, knowledge diffusion, and social cohesion (Morales et al. 2019; Niang et al. 2022). From this perspective, the CE is a compelling sustainable alternative, promising to maintain or even increase employment at the local level.

In response to this need for territorial anchoring and systemic coordination, we introduce the notion of Territorial Circular Ecosystem (TCE), as theorised by Bourdin and Torre (2025). This framework integrates economic, environmental, spatial, and institutional components into a coherent logic grounded in place-based governance. It rests on three foundational pillars: collective governance mechanisms, the articulation of geographical and organised proximities, and the active involvement of a diverse range of local stakeholders—including businesses, local governments, research institutions, civil society organisations, and residents. These elements jointly create the conditions for a transition towards durable and adaptive circular practices. The TCE framework does more than describe technical

configurations. It enables an analytical understanding of the social, institutional, and material relations that underpin circular dynamics at the territorial scale. It encourages the identification of interdependencies among actors, the mapping of material flows, and the recognition of coordination bottlenecks that may hinder the full realisation of circularity. The framework also opens space for critical reflection on governance, legitimacy, and the negotiation of trade-offs among stakeholders with differing priorities or capabilities (Chembessi et al., 2024).

In this context, this article develops a conceptual reflection on the TCE. It proposes an examination of the internal and external relations that shape such systems through a dual focus on the structure of interactions (links and nodes) and the nature of proximities (both geographical and organised). Our objective is to clarify the theoretical and institutional architecture of the TCE while identifying the operational implications for policy, local coordination, and long-term sustainability. Ultimately, the article aims to offer a framework capable of guiding the design, evaluation, and governance of circular strategies that are adapted to local contexts and embedded in broader systemic transformations.

The first section defines the territorial and systemic dimensions of CE relations and outlines the role of proximities, cooperation, and spatial anchorage. The second section introduces the conceptual framework of the TCE, focusing on its core components, institutional foundations, and types of network relations. The third section examines an empirical case to demonstrate how material exchanges and social relations contribute to the formation and evolution of a local circular ecosystem.

2 The Territorial and Systemic Dimension of Circular Economic Relations

2.1 A Shift From Sectoral Approaches to Territorial Perspectives

Debates on the Circular economy (CE) have traditionally centred around sector-based or firm-level innovations. Various frameworks, such as eco-design, industrial symbiosis, cradle-to-cradle, and life-cycle assessment, have emerged from a technical understanding of circularity. These approaches have achieved significant progress in identifying product design stages, optimising material recovery, and reducing input intensity (Geissdoerfer et al. 2017; Kirchherr et al., 2017). At the firm level, they have facilitated the implementation of circular business models based on reuse, repair, recycling, or product-as-a-service strategies. However, these approaches often focus on isolated actors or closed production-consumption cycles, frequently overlooking the importance of space, coordination, and local governance in structuring viable circular ecosystems (Bourdin and Jacquet 2025).

The implicit assumption underlying many sectoral CE models is the potential for universal deployment. Circularity is therefore treated as a modular solution that firms can replicate regardless of context. This perspective reduces the territory to a mere background variable or logistical constraint, rather than recognising it as a fundamental dimension of circularity. Yet empirical evidence increasingly

indicates that CE trajectories are influenced by the spatial and institutional environments in which they evolve. In practice, many circular initiatives succeed when they leverage local complementarities, institutional support, and embedded networks of cooperation. Conversely, they encounter failure or stagnation when these conditions are absent or fragmented (Chembessi et al., 2024; Rajaonson and Chembessi 2024).

Recent contributions in territorial economics and regional development studies propose reframing CE as a spatially embedded process. Territories do not merely host circular activities; they shape them through institutional capacities, resource availability, actor configurations, and historical legacies (Davies et al. 2024). The concept of the TCE emerges from this reframing (Bourdin & Torre, 2024). It highlights the interdependence between circular practices and place-based conditions and stresses the necessity of a system-wide approach grounded in relational geographies rather than fragmented technical fixes (Lambert 2024; Ersoy and Lagendijk 2024).

The territorialisation of CE involves redefining both scale and governance. While many circular solutions have focused on national or global supply chains, territorial approaches aim to anchor flows at smaller scales. This anchoring facilitates the design of shorter loops for waste recovery, energy transformation, and material reuse. As Chembessi et al. (2024) point out, this approach necessitates a dense network of local actors—including SMEs, local authorities, consular chambers, and civil society organisations—capable of collaborating through proximity and shared norms. Their analysis underscores how the degree of territorial integration determines the effectiveness and legitimacy of circular strategies. Ravikumar et al. (2024)' work is very useful because authors discuss Life Cycle Analysis (LCA) for CE beyond the micro level and identify meso/macro methodological challenges, including stakeholder behavior, rebound, and system-boundary issues. However, LCA remains an assessment device and cannot replace the governance, coordination, and legitimacy processes through which territorial integration is built.

Moreover, the shift from sectoral to territorial logics brings new challenges into focus. Circular initiatives must now navigate spatial constraints, socio-political dynamics, and the symbolic representations attached to specific places. In Brussels, for instance, Lambert (2024) illustrates how competing imaginaries of CE influence the inclusion or exclusion of local actors and practices. From this perspective, the territory is no longer a neutral backdrop; it becomes a contested and strategic space where circularity reflects power relations, collective aspirations, and political compromises.

2.2 Circularity as a Spatially Embedded Process

The deployment of circular economy (CE) strategies often hinges on infrastructures, actors, and material availability within a specific spatial context. Circularity does not operate in a vacuum; it necessitates logistical arrangements, technical capacities, and institutional frameworks tailored to the unique characteristics of a given territory. The functioning of resource loops depends on the integration of production, consumption, collection, and recovery processes, which are challenging to replicate uniformly

across different regions. Numerous empirical studies (Marjanović and Williams 2024; Rajaonson and Chembessi 2024; Sæther 2024) now confirm that these loops require strong spatial coherence and institutional coordination to function effectively.

For example, in the case of construction minerals in Oslo, Sæther (2024) demonstrates that circularity remains incomplete when spatial mismatches persist between extraction zones, urban consumption centres, and waste treatment locations. When transport costs rise, or when facilities lack proper connections, circular initiatives lose both economic viability and environmental efficiency. These outcomes underscore a critical issue: circularity requires territorial anchoring. Without such anchoring, loops remain fragile, fragmented, or dysfunctional. The success of CE policies becomes contingent upon the presence of territorially adapted systems, rather than the intrinsic quality of individual technologies or sector-specific programmes.

Territorial anchoring involves more than just logistics; it also encompasses socio-political configurations that enable or constrain actor coordination. In many areas, particularly those affected by deindustrialisation or demographic decline, circular transitions encounter specific structural barriers. Marjanović and Williams (2024) explore this phenomenon in Parkstad Limburg (Netherlands) and Satakunta (Finland). In both regions, local authorities attempt to initiate circular projects in response to economic contraction and the need for urban regeneration, yet they face obstacles such as institutional fragmentation, reduced financial autonomy, and limited civic engagement. These conditions diminish the capacity of local systems to stabilise circular dynamics over time.

This territorial embeddedness leads to significant heterogeneity across regions. As Rajaonson and Chembessi (2024) illustrate in their comparative study of Canadian local governments, CE implementation varies widely depending on the density of public-private partnerships, the presence of intermediary actors, and the quality of local planning frameworks. In some cases, municipalities benefit from long-standing traditions of cooperation, which facilitate the alignment of circular goals with broader territorial strategies. In others, fragmented mandates, budgetary instability, and institutional mistrust prevent CE practices from reaching maturity.

Recent research also highlights the role of urban–rural linkages in shaping the scope and feasibility of circular policies. In regions characterised by urban sprawl or functional disconnections between municipalities, coordinating resource flows is challenging. Davies et al. (2024) address this issue in their analysis of shrinking cities, where the spatial dispersion of actors impedes efforts to develop circular strategies based on closed-loop material flows. The disconnection between place-based needs and planning instruments further weakens the integration of CE into territorial development. These findings reinforce the idea that circularity should be conceptualised as a spatially embedded process, heavily reliant on the relational architecture of each territory. Technical innovations gain meaning and sustainability only when integrated into institutional systems capable of managing complexity, mediating conflict, and ensuring long-term coordination. Territories lacking these capacities struggle to move beyond experimentation or symbolic commitments.

2.3 The Role of Proximities in Enabling Coordination

The coordination of actors is a fundamental condition for the development of robust circular ecosystems. This coordination does not occur spontaneously; it relies on structural factors such as proximity, trust, and institutional infrastructure. The concept of proximity, central to territorial economy and innovation studies, has gained renewed relevance in circular economy research. It facilitates the analysis of spatial and relational configurations that support cooperation, facilitate information flow, and strengthen collective action (Torre and Rallet 2005; Chembessi et al., 2024).

Geographical proximity refers to the physical distance between actors. When firms, public bodies, and civil society organisations share the same territory, opportunities for interaction increase. Face-to-face meetings become easier, shared routines emerge, and misunderstandings are more easily resolved. This form of proximity fosters learning through interaction and reduces transaction costs. In the context of the circular economy, it plays a vital role in organising material loops, where waste producers, recyclers, and final users must coordinate collection, transformation, and redistribution processes (Torre and Gallaud 2022). Empirical studies confirm the importance of geographical co-location. Chembessi et al. (2024) and Niang et al. (2022) show that co-located firms involved in circular practices form denser and more resilient networks. Their exchanges of materials and information benefit from spatial contiguity, reducing delays, enhancing trust, and supporting reactivity in times of stress.

However, geographical proximity alone does not guarantee coordination. In many cases, actors may share a space without cooperating due to diverging interests, conflicting norms, or institutional fragmentation. This is where organised proximity becomes essential. This second form of proximity refers to the capacity of actors to connect through shared cognitive frameworks, rules, routines, and organisational affiliations (Torre and Wallet 2014). It enables coordination beyond spatial co-presence and supports the emergence of coherent systems of collective action. Organised proximity often manifests through governance bodies, project-based coalitions, professional associations, or collaborative planning initiatives. It contributes to alignment among actors by offering shared meanings, stable expectations, and institutionalised procedures (Torre and Gallaud 2022). In the circular economy context, it facilitates the standardisation of recovery processes, the definition of quality norms for secondary materials, and the design of joint investment schemes for infrastructure.

Recent contributions highlight the complementarity between the two forms of proximity. It is from their combination that the dynamics of the CE are born, because they are based on obvious technical dimensions, in terms of industrial symbioses or local resources for example, but also on the importance of networks of cooperation or trust between local actors, as well as the involvement of public or local authorities. In their study of CE transition pathways in Canada, Rajaonson and Chembessi (2024) demonstrate that successful local initiatives emerge when both types of proximity reinforce each other. Geographical closeness ensures operational fluidity and supports informal exchanges, while organised proximity stabilises relationships and institutionalises trust. In contrast, isolated circular initiatives tend to collapse or remain marginal when spatial dispersal combines with institutional fragmentation (Chembessi et al. 2025).

Moreover, various proximities foster the emergence of intermediaries who play a vital role in connecting dispersed actors, translating regulatory frameworks, and mediating conflicting interests (Bourdin and Nadou 2020). These actors, whether institutional (e.g., chambers of commerce), associative (e.g., environmental NGOs), or hybrid (e.g., regional clusters), contribute to the cohesion and adaptability of circular ecosystems. Their actions rely on a dual insertion: they must remain embedded in local dynamics while maintaining linkages with broader networks. Their position reflects the very logic of the local system, where proximity relations provide the scaffolding for systemic coordination (Chembessi et al., 2024).

3 On the Various Dimensions and Components of a Territorial Circular Ecosystem (TCE)

3.1 Earlier Attempts

Despite the wealth of empirical examples and theoretical literature available, a comprehensive conceptualisation of what defines a circular ecosystem at the local level remains notably absent. Several local production models and systems tend to focus on specific domains, such as production and innovation dynamics (e.g., industrial clusters: Porter 2003; Giuliani and Bell 2005), environmental performance through resource flows (e.g., industrial symbiosis: Chertow 2000; Jacobsen 2006), or sectoral transitions in green technologies (e.g., green clusters: Harris and Albrecht 2015). However, few efforts have successfully integrated all these dimensions—economic, ecological, spatial, and institutional—into a cohesive territorial framework. Additionally, aspects of governance, coordination among diverse stakeholders, and long-term social integration remain insufficiently explored in all these approaches (Arfaoui et al. 2024; Chembessi et al., 2024). This gap is all the more striking given the strong influence of transition studies and, in particular, the Multi-Level Perspective (MLP), which has become a dominant framework for analysing socio-technical transitions (Geels 2002, 2004; Geels and Schot 2007). The MLP provides a powerful heuristic to understand interactions across niches, regimes, and landscape pressures, and it shares with our approach a systemic understanding of transition dynamics, institutional change, and path dependence. However, its main analytical focus remains on socio-technical reconfigurations across levels, whereas the TCE perspective (Bourdin and Torre 2025) places greater emphasis on the territorial organisation of circular practices, the role of geographical and organised proximities, and the place-based coordination of material flows, infrastructures, and local actors. In that sense, the TCE framework is less a substitute for the MLP than a complementary lens that strengthens the territorial and governance dimensions of circular transitions.

This observation reveals both gaps in understanding and new topics for exploration. The comprehensive framework that pertains to local governance processes—such as the establishment of local networks and collaboration protocols among stakeholders—has been largely overlooked in the literature, with only a few pioneering studies addressing it (Deutz and Gibbs 2008; Boons and Howard-

Grenville 2009). While the exchange of energy and material flows and the potential conservation of local resources are critical, some authors have begun exploring the socio-economic relationships within eco-industrial parks. Chertow et al. (2008) emphasise that many exchanges in industrial symbiosis are driven by personal relationships and a cooperative mindset among managers. These insights support the notion that industrial symbioses and eco-industrial parks are socially embedded, akin to other forms of agglomeration economies, relying on social connections, mutual familiarity, and shared norms within the local industrial community. Additionally, both formal and informal institutions can significantly influence firms' behaviours, fostering sustained collaboration and exchange practices, as demonstrated by Morales et al. (2019) in their study of industrial symbiosis in the Altamira-Tampico industrial corridor in Mexico.

Two critical dimensions remain underdeveloped in these approaches, even if they are addressed by more traditional analyses. The first pertains to connections with external actors and systems. The framework does not formally acknowledge partnerships, institutional interactions, or economic exchanges that extend beyond the territory. These external connections are strategic resources for local systems, facilitating access to complementary expertise, financial or technical support, and regulatory innovations that may arise in other regions. A territorial ecosystem cannot function in complete isolation; its ability to adapt and evolve often hinges on its capacity to engage with external entities. The second missing element involves the participation of stakeholders beyond just firms and public institutions. Civil society organisations, environmental protection associations, neighbourhood groups, and informal collectives frequently influence local circular economy trajectories. These actors play a vital role in shaping local norms and are crucial in articulating conflicts or demands.

These findings underscore the necessity to reformulate the concept of local production systems—primarily based on a linear economy—to incorporate sustainability dimensions, particularly those related to the circular economy. There is a need for an analytical framework that allows for the definition and examination of the characteristics of local systems engaged in CE relationships, as well as the implementation of tailored local actions and policies based on this robust foundation, while accounting for the territorial governance arrangements that articulate and balance these pillars in practice.

3.2 What is a TCE?

The concept of Territorial Circular Ecosystem (TCE) addresses a significant conceptual and empirical gap by providing both an analytical framework and a detailed description of the system's various components, facilitating theoretical reflection and offering guidance for public policy development (Bourdin and Torre 2025). The roots of TCEs lie deeply in the enduring tradition of local production systems, dating back to the foundational ideas of Marshallian districts and progressing through to modern analyses of industrial clusters and districts (Marshall, 1920; Becattini, 2004). It also draws on advancements in Industrial Ecology (Chertow 2000; Beaurain and Brullot 2011; Paquin and Howard-Grenville 2012) and recent territorial research in CE studies (Bourdin et al., 2022; Davies et al. 2024). This heritage encompasses methodologies

related to green clusters (Belfanti & Alberti, 2022) and industrial symbioses (Ashton & Bain, 2012), which, despite their varying degrees of explicitness, adopt the principles of local production systems with an enhanced focus on environmental and circularity aspects. Nonetheless, these approaches exhibit certain limitations, necessitating a more comprehensive understanding of relationships and a deeper exploration of ecological and environmental dimensions to promote more sustainable production processes (see Torre & Bourdin, 2025).

Our aim is to develop a comprehensive analytical framework for characterising localised circular economy initiatives. The TCE is understood as a dynamic and systemic network of stakeholders and material flows interacting within a defined spatial context to enhance resource circularity and mitigate environmental externalities. The objective is to ensure that the territory possesses the necessary foundational elements to support a comprehensive circular approach, encompassing the famous 10R, but also to question the creation of value, the impact on the level of employment and the participation to territorial development processes. The overarching framework delineates the goals and pathways to achieve them. According to Bourdin and Torre (2025), "A TCE is a dynamic, interconnected set of economic players, institutions, policies, and practices within a specific territory. It collaborates to optimise resource flows, reduce waste, and promote regeneration through CE principles. Specifically, it is an integrated and dynamic network of actors (companies, public authorities, research organisations, non-governmental organisations (NGOs), citizens, etc.) and processes (eco-design, recovery, recycling, reuse, etc.) that foster economic circularity rooted in the territory. This complex structure aims to reduce the consumption of non-renewable resources, minimise waste production, and promote sustainable product life cycles."

A TCE is primarily based on three fundamental dimensions:

- Local Resources: This includes local material flows, knowledge and skills, infrastructure and logistics, and financial tools.
- Local Actors: This involves local authorities, firms and SMEs, intermediaries, research bodies, and civil society.
- Local or Decentralised Institutions: This encompasses policies and legal frameworks, local governance models, cultural norms, and incentive systems.

At the heart of the discussion on the systemic nature of Territorial Circular Ecosystems (TCEs) is the nature of collaboration at the territorial level, which is crucial for the functioning of local systems involved in circular economy dynamics. In any sustainable development territorial framework, cooperation is built on three primary forms of interactions, each essential for the system's stability and effectiveness. These forms of cooperation are often interconnected and collectively contribute to the formation of the local ecosystem:

1. Technical Cooperation: This category involves technical cooperation among productive or innovative businesses, primarily engaging firms, production units, and research laboratories. These interactions focus on the organisation of material, energy, and waste flows, facilitating the practical implementation of circular economy processes.

2. Socio-economic Coordination: This pertains to socio-economic coordination among a wider array of local actors, including private enterprises and public authorities such as municipalities, regional agencies, and decentralised state services. These relationships encompass information sharing, collaborative planning, trust-based interactions, and the definition of shared standards or regulatory compliance frameworks.
3. Cooperation with Civil Society: This form involves cooperation with civil society, including the participation of local associations, non-governmental organisations, and community groups. Their engagement enhances the legitimacy of circular initiatives and addresses issues of social acceptance. These actors can influence technical decisions, voice concerns, and shape collective preferences, thereby helping to prevent conflicts and bolster local support.

Digitalisation increasingly shapes the architecture of territorial cooperation within TCEs. Digital platforms dedicated to industrial symbioses and circular resource management can facilitate matchmaking between resource suppliers and users, improve the traceability of material and energy flows, and reduce information asymmetries among actors (Krom et al. 2022). They may also support socio-economic coordination by enabling data sharing, performance monitoring, and regulatory compliance, while offering new channels for consultation and stakeholder engagement. However, digital tools do not substitute for territorial governance or proximity-based trust. Their effectiveness depends on data quality, interoperability, critical mass, and institutional arrangements capable of ensuring transparency, inclusion, and accountability (OECD 2022). Digitalisation therefore acts as a transversal enabler of the three forms of cooperation, whose contribution remains contingent upon its embeddedness in local institutional and relational contexts.

These three forms of cooperation create interwoven networks that structure the local circular ecosystem. Their interconnectedness reflects the systemic nature of the territorial configuration and is shaped by long-term trajectories characterised by institutional arrangements, historical complementarities, and evolving power dynamics. (Reike et al., 2023; Rejeb et al. 2023). The sustainability and coherence of circular practices are thus contingent upon the density, quality, and continuity of these collaborative relationships (Fig. 1).

It is important to note that various proximities form the foundation of local relationships, fostering strong collaborative links through both geographical closeness and shared cultural or production communities. This foundation enables the innovative sharing of knowledge, expertise, and skills. Interactions within the system are influenced by the local labour market and its management by local businesses and organisations. Organised proximity also facilitates the establishment and maintenance of connections with firms or public authorities outside the local system. The dimension of industrial symbiosis is supported by the mobilisation of local resources and the management of flow exchanges and waste recycling, aligning with the three pillars of the circular economy: reduce, reuse, and recycle. Ultimately, the entire Territorial Circular Ecosystem (TCE) is guided by local institutions, including local authorities, decentralised State services, and consular Chambers.

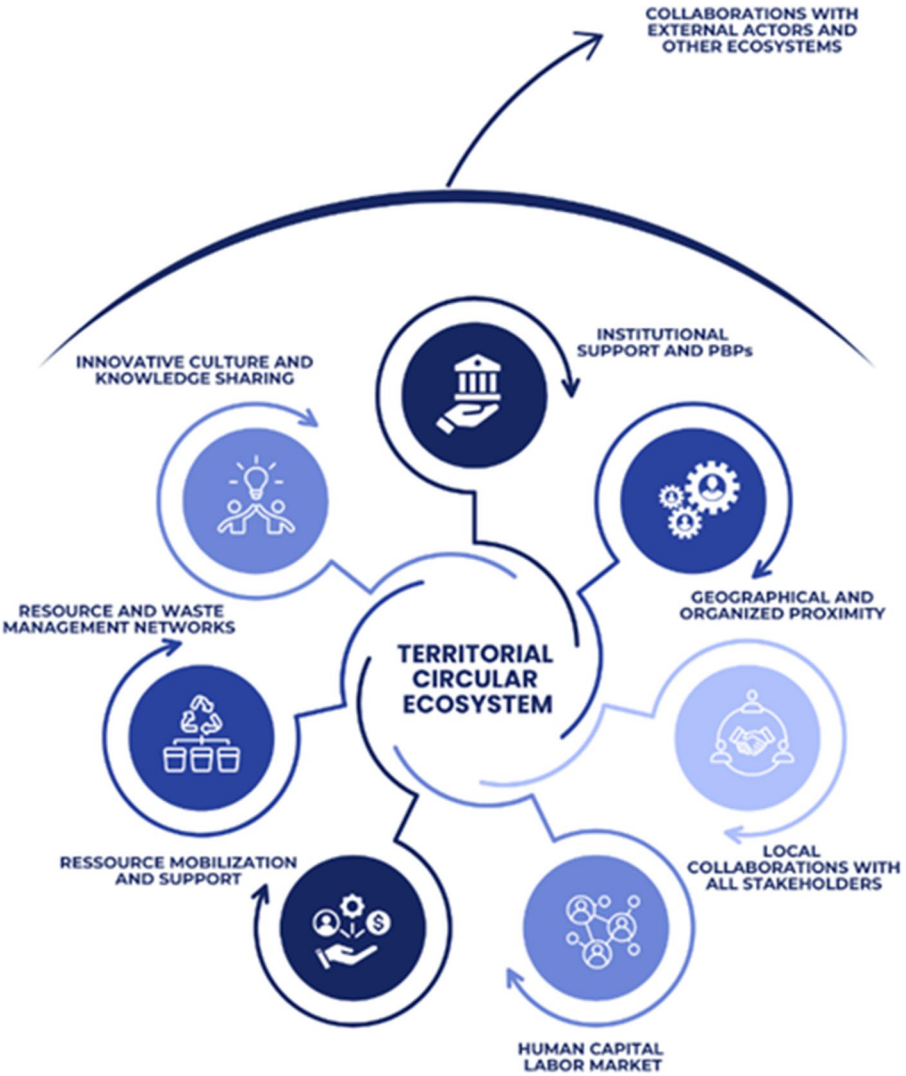

Fig. 1 Components of a Territorial Circular Ecosystem (the authors)

3.3 TCEs and Local Betworks

The networks of interactions between actors form the foundation of a Territorial Circular Ecosystem. They correspond to the three forms of cooperation previously highlighted: technical cooperation, socio-economic coordination, and cooperation with civil society. In academic studies, particularly with regard to data collection, these networks are generally divided into two main categories of flows. On one hand, there are flows of materials or energy between companies engaged in circular economy practices or symbiotic relationships. On the other hand, there are interactions of a socio-economic nature, based on market exchanges, cooperation links, or various collaborations, between

Table 1 Main components of a TCE and network relations (the authors)

Main components of a TCE	Network relations
Interactions between local actors	+++
Involvement of non-productive local actors	+++
Connections beyond the local system	+++
Role of local institutions	0
Green labels	0
Circulation of waste, energy and materials	+++
Territorial resource preservation	0
Product life cycle extension	0
Geographical and organized proximity relations	+++
Contribution to local employment	+++

productive actors or with society (Niang et al. 2022). These last two dimensions may be grouped together because they are based on links between natural persons.

These networks connect the main actors involved in a TCE: firms or establishments, laboratories, local brokers, local public authorities, consular chambers (of commerce, agriculture, or crafts), local governance bodies, local associations or groups, and external actors. By examining the different elements of a TCE, we can trace the types of terminative relationships (Table 1). These relationships can be internal or external to the TCE, and take the following forms:

- Interactions between local actors.
- Involvement of non-productive local actors (relations with civil society, associations, public authorities).
- Circulation of waste, energy and materials.
- Local employment networks.
- Geographical or organized proximity relations.

The description of this system should enable the formulation of local actions and the identification of public policy elements that support the adoption of effective CE practices. A key takeaway is that the systemic dimension is crucial; initiatives should not be viewed in isolation or disconnected from the core components of a TCE. Although it is still relatively uncommon for all the elements discussed to be present at the local level, enabling a complete and synergistic operation, it is essential to address certain bottlenecks to ensure functionality that remains connected to the local context and has a tangible impact. Otherwise, we risk encountering the phenomenon of the "white elephant," commonly observed in local systems—an initiative that may offer certain ecological or employment benefits but fails to generate a significant local impact. In addition to the lack of an economic ripple effect, which would result in growth primarily benefiting areas outside the territory due to external leakages, there is a second consequence: environmental advantages may be squandered or significantly diminished due to the failure to close the loop at the local level.

A TCE can be incomplete, which can mean two things:

(i) the set of actors necessary to achieve a perfect symbiosis is not complete within the territory; this is the most common case. This is why we refer to the metaphor

of rhizomes, which alludes to both the horizontal dimension of relations and their imperfect character;

(ii) the set of relationships between the actors that make up the TCE may be incomplete, meaning that relationships may (or may not) exist between these actors, but in any case, they do not all fall within the category of CE practices (Lastres and Cassiolato, 2005). The medium-term goal is for the territory to possess sufficient foundational components to initiate and develop a circular approach.

4 Investigate the Interconnected Nature of CE Relations in a TCE: Networks of Resources, Materials, Economic and Social Relations

To delve into the structure of a Territorial Circular Ecosystem and evaluate its various structural characteristics, as well as its resilient or rhizomic nature, we will study a specific TCE with the aim of understanding its functioning and evolution over time. The chosen case study focuses on the process of recovering municipal household waste at the Cavigny site in Normandy, France, which specialises in anaerobic digestion.

4.1 Presentation of the Case Study

The Syndicat Mixte du Point Fort (SMPF) is a public inter-municipal cooperation body responsible for waste prevention and management across 125 municipalities in the Manche department of Normandy, France. Located in Cavigny, it serves over 116,000 residents and handles selective collection, pretreatment, elimination, and treatment of waste. The methanisation process supports circular economy goals by turning waste into local resources, promoting renewable energy, and reducing pollution and greenhouse gas emissions. It involves multiple stakeholders: municipalities supplying waste, PFE managing operations, farmers using compost, and regulatory bodies ensuring environmental compliance. A residents' association participates in monitoring risks, enhancing transparency and community engagement.

The SMPF operates 14 free waste collection centers, two glass transit platforms, and a non-hazardous waste storage site with a 70,000-ton capacity. A key facility is its anaerobic digestion (AD) plant in Cavigny, which processes 72,000 tons of organic waste annually. This unit converts organic matter and green waste into biogas and compost, producing renewable energy and fertilizer. Its governance includes a syndical committee of 38 delegates from member communities, who approve budgets and set strategic directions. An executive board, led by a president and eight vice-presidents, oversees operations. The technical department, Point Fort Environnement (PFE), manages facility construction and operation.

This integrated approach demonstrates innovation in waste valorization and regional cooperation, contributing to energy autonomy and sustainable development. The TCE brings together associated actors around the mobilisation of local inputs, the reuse of by-products, risk management, and the social inclusion of local populations in the anaerobic digestion project. It involves exchanges of materials and energy, and socio-economic relations, which meet the common needs of the actors and are likely to generate positive spin-offs for the territory (Fig. 2).

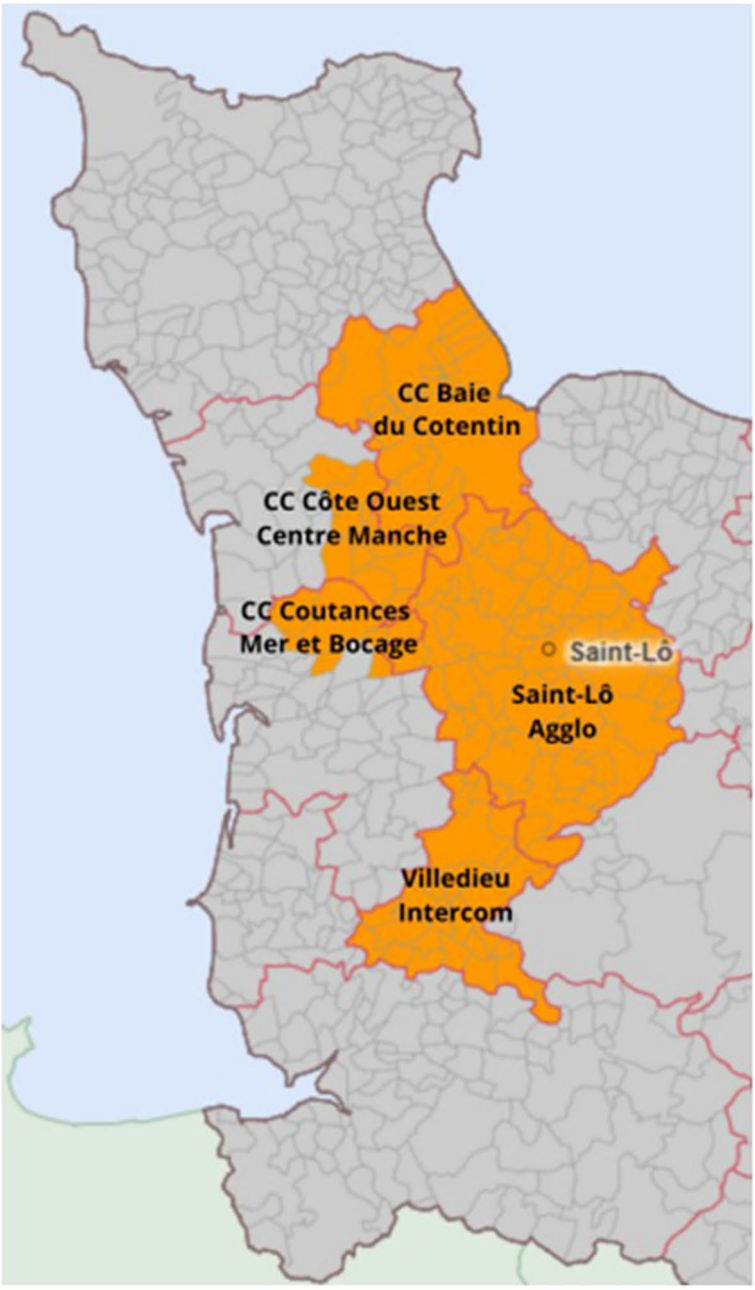

Fig. 2 Map 1. The SMPF in Normandy, France

4.2 Methodology

The study examines social networks and their evolution over time, identifying two primary types of networks: one for material flows, circulating among companies and local farmers, and another for economic exchange relationships and cooperation among local actors. The research effectively highlights and analyses the duality between energy and material flows, as well as the cooperative relationships among stakeholders.

The use of social network analysis helps to understand the structure of the TCE, its main actors, and the relationships that connect them, quantifying their number and importance. It also highlights the place and role of each actor, as well as their more or less central or peripheral positions, for example the most important or central actors, as well as those playing a more secondary role or positioned on the periphery of the system.

To highlight the dynamics of the TCE, the study spans three successive periods, each five years apart (2010, 2015 and 2020). Data are collected through semi-structured interviews, based on a group of actors identified by local authorities. As interviews progress, new actors are added if necessary, according to the snowball method, when it becomes apparent that they have significant relationships with the TCE's main actors.

To analyse the internal relations to the TCE, we use classical graph theory indices:

- The indices of betweenness and closeness centrality characterize the positions and importance of actors within the network structures. Actors with a high value of betweenness position themselves as a relay intermediary, possessing significant control over exchanges and interactions;
- Conversely, actors with high values of closeness centrality have a lower importance in networks of relationships;
- The average degree represents the average number of links involving an actor. When it is high the actors appear central and play an important role in the flow (Wasserman and Faust 1994). This indicator measures the level of connectivity, i.e., the actors with the greatest number of relationships (Freeman 1979);
- The n-clicks express the number of sub-groups observable within the network, make it possible to identify cohesive groups of actors strongly linked to each other (Borgatti 2002). The presence of many n-clicks implies a weakness of relations between actors, resulting in a non-cohesive network. In contrast, a limited number of n clicks is synonymous with solidarity, social control and information circulation.

The study first focuses on identifying the main actors within the system. These include:

- Local Authorities: These comprise municipalities or inter-municipalities, members of the Syndicat Mixte du Point Fort (SMPF), and non-member customers who deliver their waste under agreements and public contracts.

- Syndicat Mixte du Point Fort (SMPF): This Public Establishment for Intermunicipal Cooperation (EPCI) is responsible for the management and recovery of municipal waste.
- Decentralised Technical Services of the State: These services are responsible for enforcing regulations on Classified Facilities for the Protection of the Environment (ICPE), under which the Cavigny anaerobic digestion unit is categorised.
- Two Co-product Companies: These are professionals involved in the reuse of anaerobic digestion by-products.
- Local Farmers: They utilise the compost produced through the anaerobic digestion process.
- An Environmental Protection Association: This association represents local and neighbourhood populations directly affected by waste collection, transport, and treatment activities.

4.3 Exchange of Materials and Energy

In the TCE of Cavigny, the local exchange of materials and energy is facilitated by a productive partnership network. This network involves, on one hand, the municipalities that supply household biowaste to a public body, which processes it to produce compost and biogas converted into electricity. On the other hand, it includes various local companies specialising in recycling and reusing waste and co-products. These co-products are then sold to two companies that specialise in purchasing and marketing products from sustainable and circular activities. Commercial relations with supply customers are conducted based on public procurement contracts. The electricity generated is injected into the public distribution network by the energy supply company to be provided locally to consumers. Compost, purchased by another private company, is sold to farmers for local use on farms as organic fertiliser.

The initial finding is that the network is dense, with very few gaps, and a high-density index from the early years of the anaerobic digestion project's development (Table 2). It evolves further by becoming denser, representing more than 65% of

Table 2 Characteristics of the material and energy exchange network (the authors)

	Categories of actors	Average degree		
		2010	2015	2020
Network Composition	Local authorities	17	11	8
	Project leader	20	15	10
	Co-product companies	4	4	4
	Farmers	2	2	2
Network Size	Network structural Indicators			
	No. of actors	22	16	12
	No. of links	266	120	86
Network Structure	Density	0.576	0.441	0.652
	Average degree	12.091	7.059	7.167
	N-click	2 2-clicks	2 2-clicks	2 2-clicks

possible relationships, marked by a decline in the average number of links (average degree) per actor[1]. The densification of links is particularly indicative of the intensity of various flow circulations and the cohesion in relationships between the network's actors. The detection of only two interdependent subgroups (2 n-clicks) confirms the strong cohesion in flow exchanges. These solidarity subgroups are composed of the same actors, differing only in that the farmers belong only to the first group, and the electricity company only to the second.

Mapping productive relationships allow us to analyse the average number of links involving an actor (average degree). It reveals the centrality of the company responsible for treating and transforming waste (the Project Leader), which holds the largest number of relationships (see Table 1). This company develops circular economy (CE) relationships with all local stakeholders, particularly with local authorities, which are strongly connected by the strength and number of productive relationships and social ties they maintain. It was created by local public authorities, which transferred the technical and financial responsibilities of the public municipal waste treatment service to this entity. Elected representatives are delegated to its decision-making bodies (union committee and union bureau), marking their proximity by belonging to the same organisation. The company is also geographically close to local authorities, being located in the municipality of Cavigny, at the epicentre of the TCE's administrative territory, which constitutes its operational area of action with a territorial network of waste treatment facilities.

The least active players in the network are those involved in the development of co-products (companies and farmers), with a limited number of links and only occasional trade exchanges, which vary in frequency over the years. These actors are mainly marked by the significant geographical distance of the companies, whose scale of action is at the regional level. Nevertheless, the compost is distributed locally to farmers within a maximum radius of 30 km from the epicentre of the approach.

The evolution and development trajectory (in 2010, 2015, and 2020) of the productive partnership network is illustrated by their graphs (Fig. 3). These graphs include two categories of actors mentioned above, excluding the decentralised services of the State and the local association, as they are not involved in the exchange of materials and energy. Each category, represented by the colours of the nodes, corresponds to a number of actors connected to the network. The size of the nodes reflects the number of links adjacent to each actor, proportionate to its degree value, indicating its influence and the importance of its involvement in the exchange of material and energy flows.

The position of intermediary actors within the network is measured by the betweenness and Closeness centrality (Fig. 4). Niang et al. (2021, 2022) have shown the positioning of the project leader (PFE-SMPF, UT1-SMPF and UT2-SMPF) as a major influencer, with the ability to connect all the actors within its municipal organic waste methanisation network in Cavigny. This position corresponds to its status as an inter-municipal cooperation establishment, created by the local authorities that have

[1] The decrease in the number of actors is due to the territorial reform of 2015, which led to a partial reformatting of the institutions and the merger of several of them.

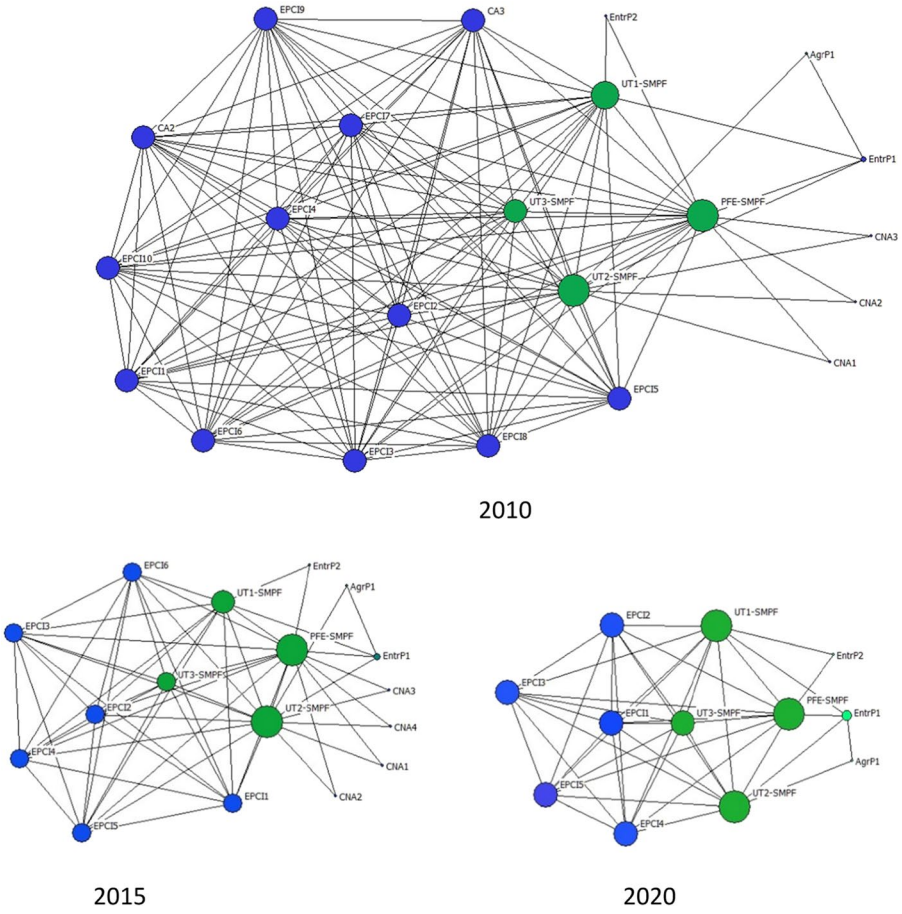

Fig. 3 Evolution of the network of materials and energy (2010-2015-2020) (the authors). Legend: Local authorities (EPCI: inter-municipalities members of the SMPF; CA: municipalities members of the SMPF; CNA: municipalities nonmembers of the SMPF); SMPF - Project leader (EPF-SMPF: general direction; UT1-SMPF: methanization unit; UT2-SMPF: Waste collection centers; UT3-SMPF: Sorting center); Co product companies (EntrP1: compost company; EntrP2: electricity company) ; Local farmers (AgrP1)

transferred it and entrusted it with the technical and financial powers for the treatment and recovery of their waste.

By facilitating connections between various actors from different fields who were not initially expected to collaborate, the project leader contributes to the structuring role of local authorities, which participate in the financing and coordination of public action. Specifically, the project leader plays this role by establishing links between the local authorities supplying inputs and the companies involved in the recovery of co-products, which occupy minor positions, as indicated by their high values of closeness centrality.

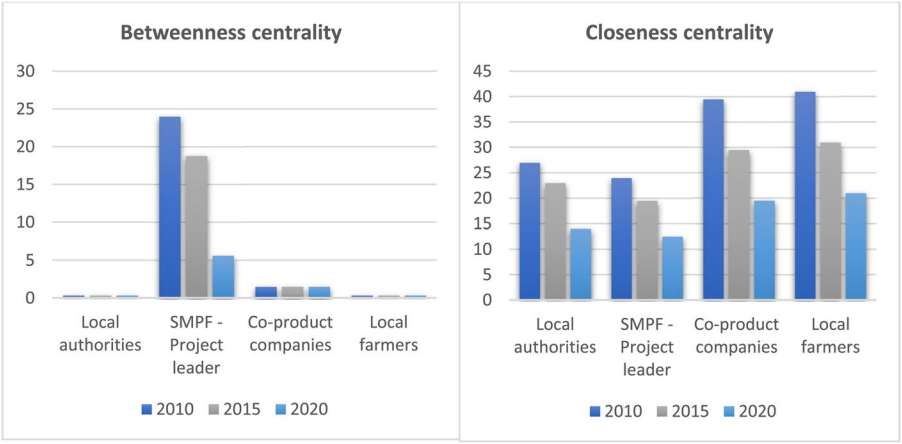

Fig. 4 The influence of various actors in the material and resources exchange network (the authors)

4.4 Social Ties are Created and Developed in Socio-economic Relations

Interviews with the actors of the TCE revealed a collective activity often based on social, interpersonal, friendship or family ties, conducive to the exchange of physical flows of materials and energy and the circulation of information between local partners of CE synergies. We observe a network of social relations, communication and information exchanges about rules and good practice of anaerobic digestion, the efficient mobilization of inputs, the management of environmental externalities, nuisances and health risks. This network brings together local authority officials, their representatives in the management bodies of the waste treatment establishment and its employees, as well as the decentralized technical services representing the State and a local association, supposed to ensure the proper regulatory conduct of the approach and the control of risks and the negative impacts of the process of anaerobic digestion[2].

Social interactions are of two types. Formal interactions take place within the deliberative assembly of the local authority union committee, which monitors the site and meets at least once a year, and the monthly meetings of the union committee of the elected members of the SMPF. These regulatory governance bodies offer in particular a framework for exchanges, information on the actions taken for risk management and the social inclusion of local residents in the process. But in addition to these formal frameworks for dialogue and consultation, more or less formal meetings take place every two weeks between the managers of the anaerobic digestion site; the managers of the local association are invited to these discussions, in particular about the odors and noise pollution linked to the traffic of waste transport trucks and their social acceptation.

[2] Farmers do not belong to the network of social relations. They do not participate in any SMPF body, nor in the site monitoring commission, nor in any SMPF meeting. The only relationship is the use of compost through SEDE (now Véolia environnement), the company that buys and sells compost to farmers.

Table 3 Dynamic characteristics of the social relations network (the authors)

	Categories of actors	Average degree		
		2010	2015	2020
Network Composition	Local authorities	35,70	23,56	21,53
	Project leader	19.95	13.92	12.92
	State services	7.35	7.50	7.53
	Local association	8.40	8.57	8.62
Network Size	Network structural Indicators			
	No. of actors	21	15	14
	No. of links	286	136	118
Network Structure	Density	0.681	0.648	0.648
	Average degree	13.619	9.067	8.429
	N-click	2 2-clicks	2 2-clicks	2 2-clicks

The size of the network of social relations is different from that of the network of productive partnership, with fewer actors, and higher degree values (see Table 3). Social relations are also organized in two cohesive sub-groups (2, 2 cliques), according to the closeness ties of the actors, and their belonging to the governance bodies of the CE approach. In the first solidarity group local authorities and their representatives interact with all the network's actors, during five or six deliberative annual meetings of the union committee, or meetings of the union bureau and the operational teams of the SMPF. The other sub-group brings together the members of the site monitoring commission, controlled by the decentralized services of the State, including the elected representatives of the union bureau and the employees of the establishment carrying out the project, as well as the residents' association and the Town hall of Cavigny.

The syndicate operating the anaerobic digestion project and the local authorities appear to be the actors maintaining the most relations within the network (see Table 3). Social relations were particularly dense at the start of the project's development cycle, with a density value that subsequently decreased and stabilizes at a consistently high level. This result suggests the importance of the local governance mechanisms of dialogue and consultation, put in place at the launching of the project, which have made it possible to maintain social ties related to productive relations.

Local authorities play a central role in socio-economic exchange relations. This is all the more important for the Town hall of Cavigny, as it acts as an intermediary with the managers of the waste treatment company and the project leader (Fig. 5). Moreover, the municipality of Cavigny hosts the anaerobic digestion facilities on its territory, giving it an important role in decision-making, by participating by right in the site monitoring committee and all the governance bodies of the process.

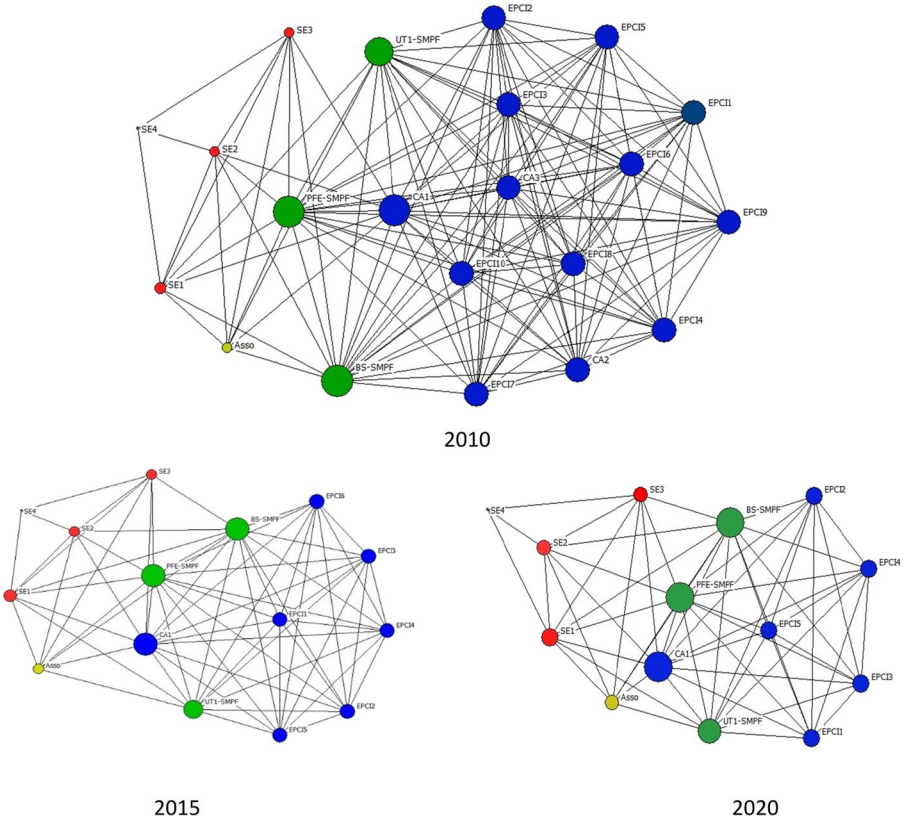

Fig. 5 Evolution of the network of social relations (2010-2015-2020) (the authors). Local authorities (EPCI: inter-municipalities members of the SMPF; CA: municipalities members of the SMPF); SMPF - Project leader (EPF-SMPF: general direction; BS-SMPF: union committee; UT1-SMPF: methanization unit; UT2-SMPF: waste collection centers); Decentralized services of the State (SE) ; Local association (Asso). Legend: the nodes of the networks represent the actors, the colors of the nodes the categories of actors connected to the networks. The size of the nodes represents the number of relationships involving an actor in proportion to its degree value, and indicates the influence and importance of the actors in the network of social relations

Based on its communication and information exchange relations with all network actors, the Town Hall of Cavigny collaborates with the project leader to play a structuring role and to build connections between the major and less important players within the network. This is particularly evident with the decentralised services of the State and the local association, which have a more limited role with higher values of closeness centrality (Fig. 6), due to their weak interactions with local authorities at the level of the trade union bodies. However, the local association, while not very active on a daily basis, is involved in representing local populations by periodically participating in the site monitoring committee, deliberative general assemblies, and informal meetings.

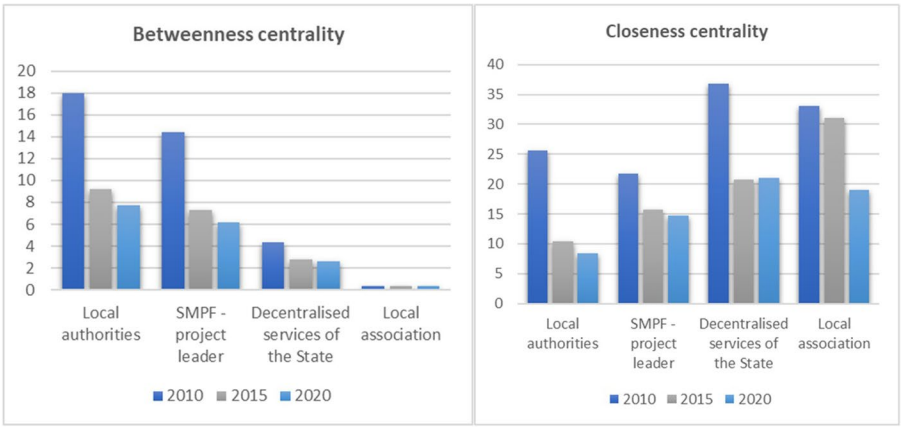

Fig. 6 The influence of various actors in the network of social relations (the authors)

4.5 Organized Proximities that Allow Collective Action and Conflict Management

The notion of organized proximity refers both to the intensity of interactions between actors, which reveals the extent to which they are caught up in a bundle of relationships (logic of belonging), and to the fact of sharing common values or projects (logic of similarity). It can take place between local actors, or at a distance and allows us to understand the logic behind the actions carried out jointly, as in the context of the implementation of CE practices within a TCE. In order to quantify the importance of organized proximity relationships of belonging within the Cavigny anaerobic digestion system, and therefore to understand the structure of the internal governance mechanisms, we measure the frequency of social interactions between members of decision-making bodies of the system. This indicator allows us to highlight which actors have the highest level of organized proximity, and therefore play a central role in the interaction process, or to determine the position of other categories of local actors.

We study the frequency of social interactions maintained each year by the main decision-making bodies, according to their frequency of participation to face-to-face formal and informal meetings (Fig. 7 presents the distribution of the interactions).

Social interactions primarily occur within the Union committee. Accounting for more than half of the frequency of relationships (52%), these interactions involve local authorities that delegate 38 of their elected representatives, maintaining direct proximity relations of belonging to the establishment they helped create to pool the treatment of their municipal waste. Along with the Union office (12.33%), these are the two organisational entities that enable local authorities to meet face-to-face on a more or less regular basis to decide on strategic orientations concerning the governance of material and energy flows. The governance of the establishment is also shared with the operational entity of employees, who are responsible for implementing the decisions made by elected representatives in daily anaerobic digestion activities. This indirect relationship is managed by salaried managers who regularly meet with both parties during weekly meetings of general management, as well as those of the union committee and union office.

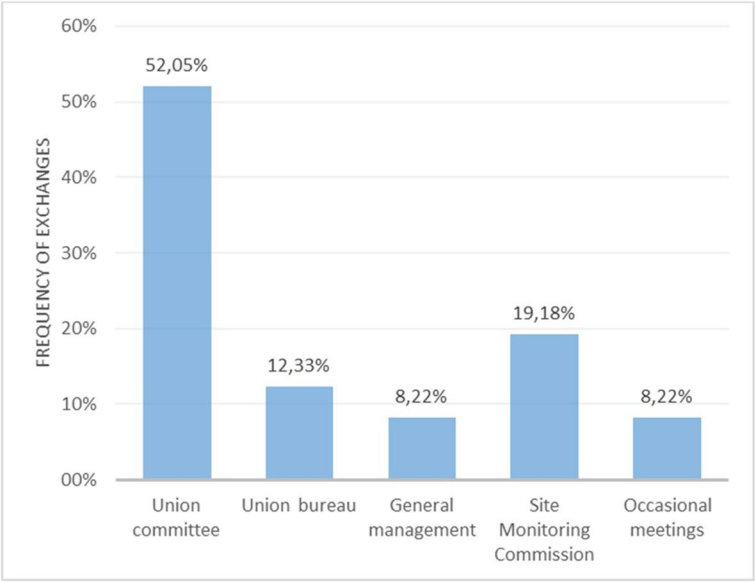

Fig. 7 Frequency of face-to-face exchanges per year between decision-making bodies (the authors)

Meeting more frequently fosters a climate of trust conducive to consultation based on common operating rules. Co-location plays a role in bringing local authorities closer together, helping to overcome geographical distances, facilitate contacts and exchanges, and social interactions within the same organisation. However, their belonging to the same establishment is primarily based on shared values regarding the recovery of municipal bio-waste in a circular economy logic. Local authorities unite around a common ideal to create a circular territory, enabling the production and consumption of renewable energy and nitrogenous organic fertilizers from local biomass.

4.6 Geographical Proximity: The Spatial Dimension of a TCE

What are the different territorial scales of action of the actors in a Territorial Circular Ecosystem (TCE) (regional, departmental, and local scales)? What is its relevant size? To quantify and qualify these links and their impact on actors' behaviours, we analyse the structure of geographical proximity relations within the local network of members engaged in circular economy (CE) practices in Cavigny. The average number of connections (average degree) is recorded for each actor to calculate the total proportion of relationships with other actors according to their geographical distance from the epicentre of the anaerobic digestion process (Table 4). This approach considers both productive and social relations.

The analysis reveals that in this TCE, most interactions—whether productive or social—between socio-economic actors occur at the local level (<45 km), with 58% of relations within the inter-municipal territories falling under the competence of the municipal waste treatment syndicate. Local relations appear to be more structuring compared to departmental and regional relations, which account for only 28% and

Table 4 proportion of relationships according to the distance between CE actors (the authors)

Geographical scale of action	Project development periods						Total
	2010		2015		2020		
	Relationship Type						
	Product	Social	Product	Social	Product	Social	
Local (0 to 45 km)	56%	69%	54%	57%	49%	56%	58%
Departmental (45 to 100 km)	15%	31%	20%	43%	24%	44%	28%
Regional or national (+ 100 km)	30%	0%	26%	0%	26%	0%	14%
Total	23%	20%	14%	14%	14%	14%	100%

14% of interactions, respectively. This strong geographical proximity highlights the importance of permanent co-location related to CE practices, particularly in this case between the waste treatment company, local authorities that supply them, and the local association for environmental protection, which represents local populations in the decision-making process.

This result can be explained by the smaller number of actors deployed at geographically distant scales, mainly decentralised (departmental) services of the State, which periodically meet with the actors in charge of the anaerobic digestion project during annual inspections to produce reports presented once a year to the members of the site monitoring commission. Most importantly, it reveals the critical nature of local relations. Specifically, commercial exchanges of co-products with distribution companies account for 30% of productive interactions at the regional level, particularly with the national energy supply company that buys back electricity to inject into the distribution network. Characterised by the absence of social relations at this scale, exchanges are conducted through occasional trips to the processing site, particularly for farmers using compost within a maximum radius of 30 km from the anaerobic digestion unit.

Most relations are driven by local authorities and the project leader. By acting as intermediaries, they help structure the network, maintain social ties, and ensure the effectiveness of relations, even with partners far from the epicentre of the process. This preponderance of local-level exchanges highlights the relevance of geographical proximity relations. These are sought for their virtues in terms of circularity within a short territorial loop, promoting the pooling of skills and equipment for the collection, treatment, and recovery of municipal biowaste. They help reduce transaction costs and environmental damage. Decisions are made on-site, establishing system governance, but external inputs are also necessary. Regional or national productive relations appear more important than social ones. In this context, new information and communication technologies (ICT) are often used to maintain customer-supplier relationships at a distance and limit temporary face-to-face meetings.

It should be noted that geographical proximity to the CE process is imposed on other actors external to the project, such as local populations subjected to the vicinity of the mechanisation activity facilities in Cavigny. Often, this situation is unacceptable for local actors due to consequences in terms of noise and odour pollution, as well as environmental and health risks. This imposed proximity, leading to conflicts, sometimes hinders the smooth running of the project. In the case of Cavigny, a solution has been found with the involvement of the neighbourhood

defence association in the process of drafting projects and standards. This agreement must be constantly renewed and validated through meetings held at specific times and with a regular agenda. They clearly imply other types of proximity than just geographical proximity, such as organized proximity with its dimensions of sharing cultures and setting up networks of economic and social actors, beyond the sole productive dimensions.

4.7 Coupling Effects Between Organised and Geographical Proximities

The analysis of organised and geographical proximities is better understood as an examination of interdependent dimensions of the TCE rather than separate analytical layers. The Cavigny case shows clear coupling effects between the configuration of social networks and their territorial embeddedness. Dense organised proximity relations, captured through repeated interactions within governance bodies, strengthen the stability of geographically proximate exchanges. Regular face-to-face meetings sustain trust, shared rules, and conflict-management routines, and these relational foundations help secure the continuity of short-loop material and energy flows.

The relationship also works in the other direction. Geographical proximity supports the consolidation and reproduction of organised proximity. Spatial co-location lowers coordination costs, facilitates recurrent formal and informal contacts, and reinforces institutional belonging. In Cavigny, the concentration of key actors within a limited territorial radius supports both the operational efficiency of productive exchanges and the cohesion of governance arrangements. Social networks are territorially anchored, and territorial proximity becomes effective through organised interaction. This reciprocal reinforcement shows that circular coordination cannot be reduced to physical distance alone or to social connectedness considered in isolation. The effectiveness of the TCE depends on the articulation between network structures and territorial anchoring, that is, on the way organised and geographical proximities become mutually supportive over time.

5 Conclusion

In this paper, we have presented and studied the notion of a Territorial Circular Ecosystem (TCE), which allows us to consider both the spatial and systemic dimensions of Circular Economy relations and practices. We have demonstrated that this approach helps identify the main actors, resources, and institutions playing significant roles at the local level, as well as the different categories of coordination underpinning the structure of these relationships: technical coordination, coordination between productive actors, or with civil society actors. Using the case study of anaerobic digestion in Cavigny, we presented tools that help penetrate this rhizomic structure. The social networks approach enables us to understand the relationships binding different local actors, in terms of productive and socio-economic links, and to identify the most crucial actors who occupy a central place, or those in a more peripheral situation. Finally, the analysis of proximities helps understand the drivers of their alliances or common behaviours (organised proximities), as well as their

spatial anchoring and local or extraterritorial alliances (geographical proximities), and, more broadly, the coupling effects between social network structures and territorial embeddedness.

These results lead us to better comprehend the inner workings of a TCE structure and to draw the first elements of reflection for economic policies aimed at implementing sustainable development processes based on the circular economy. The complexity of internal relations is highlighted by the fact that, while waste treatment companies play a central role in the network of material and energy flows, it is the local public authorities, particularly municipalities, that hold a central position in the socio-economic exchange network. This underscores the decisive nature of the local dimension, whether it be the local circulation of resources, materials, or energy flows within a small geographical area, or exchanges between key actors in the process, such as authorities responsible for governance, companies in charge of symbiosis, or providers and users of recycled products. In our case, the local scale is not simply the spatial setting of circular practices; it is the level at which coordination is made possible, conflicts are managed, and circular routines are stabilised over time. Maintaining cohesion between local actors is also essential, in terms of organised proximity, with this cohesion resting on repeated interactions, exchange relationships, interpersonal ties, and a shared vision of the CE process. This relational cohesion is a core condition of TCE durability and operational effectiveness. This cohesion extends beyond the circle of productive actors and must also involve local neighbours, who could oppose the installation of industrial CE structures or block activities. For this reason, the inclusion of residents and local associations should be understood as a central component of territorial circular governance, rather than a secondary issue of social acceptability.

The first attempt made here to analyse the properties of a TCE deserves to be extended, particularly by using a greater number of tools allowing a more refined assessment of the different characteristics of these systems. For example, it would be interesting to investigate geographical proximity relations further, not only by considering distance but also by studying access times linked to infrastructure such as roads or railways. A further extension would be to complement this spatial approach with a time-geography perspective (Hägerstrand 1970), in order to analyse how temporal constraints shape the feasibility of circular exchanges and symbioses. Such an approach could help identify capability constraints (e.g., storage capacity or technical limits), coupling constraints (e.g., collection schedules, treatment windows, coordination timing), and authority constraints (e.g., regulatory procedures, access rights, contractual rules) that delimit feasible circular loops, including when actors are geographically close. From the perspective of organised proximity relations, beyond the interactions presented in this article, it would be interesting to evaluate the levels of adherence to common values in terms of CE practices, which may differ depending on the categories of actors, using tools such as discourse or text analysis. Finally, it would be necessary to examine much more precisely the interactions with actors outside the TCE at different geographical levels and study the reasons that motivate these relations and their maintenance over time.

Author contributions AT had the idea of the paper, conceived the structure of the manuscript and managed the writing process. AN made the computations and wrote the technical part. SB wrote the theoretical part and modified some parts of the manuscript.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Arfaoui N, Bourdin S, Torre A, Vernier MF, Vo LC (2024) Geographical and organised proximities influencing circular economy practices: the closer partners, the better? Reg Stud 58(12):2485–2500

Ashton WS, Bain AC (2012) Assessing the "short mental distance" in eco-industrial networks. J Ind Ecol 16(1):70–82

Ayres RU, Ayres LW (2002) A handbook of industrial ecology. Edward Elgar

Beaurain C, Brullot S (2011) L'écologie industrielle comme processus de développement territorial: une lecture par la proximité. Revue d'Economie Régionale Urbaine, (2), 313–340

Becattini G (2004) Industrial districts: a new approach to industrial change. Edward Elgar, Cheltenham

Belfanti F, Alberti FG (2022) Clusters and sustainable development: a systematic literature review. Int J Compet 2(2):137–159

Blomsma F, Brennan G (2017) The emergence of circular economy: A new framing around prolonging resource productivity. J Ind Ecol 21(3):603–614

Boons F, Howard-Grenville J (eds) (2009) The Social Embeddedness of Industrial Ecology. Edward Elgar Publishing

Borgatti SP (2002) A Statistical method for comparing aggregate data across a priori groups. Field Methods 14(1):88–107

Bourdin S, Jacquet N (2025) Closing the loop at the local scale: Investigating the drivers of and barriers to the implementation of the circular economy in cities and regions. Ecol Econ 231:108542

Bourdin S, Nadou F (2020) The role of a local authority as a stakeholder encouraging the development of biogas: a study on territorial intermediation. J Environ Manage 258:110009

Bourdin S, Torre A, van Leeuwen E (eds) (2024) Regions, Cities and the Circular Economy: Theory and Practice. Edward Elgar Publishing

Bourdin S, Torre A (2025) Economic geography's contribution to understanding the circular economy. J Econ Geogr 25(2):293–308

Bourdin S, Galliano D, Gonçalves A (2022) Circularities in territories: opportunities & challenges. Eur Plan Stud 30(7):1183–1191

Chembessi C, Bourdin S, Torre A (2024) Towards a territorialisation of the circular economy: the proximity of stakeholders and resources matters. Camb J Reg Econ Soc 17(3):605–622

Chembessi C, Bourdin S, Torre A, Beaurain C (2025) Creating Territorial Value Through Circular Economy: Why Proximities Matter? *Business Strategy and the Environment*
Chertow MR (2000) Industrial symbiosis: Literature and taxonomy. Annu Rev Energy Environ 25:313–337
Chertow MR, Ashton WS, Espinosa JC (2008) Industrial symbiosis in Puerto Rico: Environmentally related agglomeration economies. Reg Stud 42(10):1299–1312
Davies JS, McGuinness D, Lehtonen M (2024) Shrinking cities and the circular economy: Planning dilemmas and democratic trade-offs. Camb J Reg Econ Soc 17(3):318–340
Deleuze G, Guattari F (1987) A Thousand Plateaus, Capitalism and Schizophrenia. University of Minnesota Press, Minneapolis, p 585
Deutz P, Gibbs D (2008) Industrial ecology and regional development: the role of networks in the emergence of symbiosis. Progress Industrial Ecol Int J 5(5–6):483–499
Ersoy A, Lagendijk A (2024) Space, institutions and policy logics: Why circular economy is not a ready-made place-based solution. Camb J Reg Econ Soc 17(3):258–277
Freeman LC (1979) Centrality in social networks: conceptual clarification. Social Networks 1(3):215–239
Frosch RA, Gallopoulos NE (1989) Strategies for manufacturing. Sci Am 261(3):144–152
Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy 31(8–9):1257–1274
Geels FW (2004) From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Res Policy 33(6–7):897–920
Geels FW, Schot J (2007) Typology of sociotechnical transition pathways. Res Policy 36(3):399–417
Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ (2017) The circular economy – A new sustainability paradigm? J Clean Prod 143:757–768
Ghisellini P, Cialani C, Ulgiati S (2016) A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. J Clean Prod 114:11–32
Giuliani E, Bell M (2005) The micro-determinants of meso-level learning and innovation: Evidence from a Chilean wine cluster. Res Policy 34(1):47–68
Hägerstrand T (1970) What about people in regional science. Transp Sociology: Social aspects Transp Plann, 143–158
Hachaichi M, Bourdin S (2023) Wheels within wheels: mapping the genealogy of circular economy using machine learning. Circular Econ Sustain 3(4):2061–2081
Harris M, Albrecht J (2015) The geography of green innovation: Clusters, networks, and public policies. Environ Sci Policy 54:1–8
Jacobsen NB (2006) Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. J Ind Ecol 10(1–2):239–255
Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: An analysis of 114 definitions. Resour Conserv Recycl 127:221–232
Korhonen J, Honkasalo A, Sepala J (2018) Circular Economy: The Concepts and its Limitations. Ecol Econ 143:37–46
Krom L, Piscicelli L, Frenken K (2022) Industrial symbiosis platforms: A review of matchmaking, governance, and digital mediation challenges. J Ind Ecol 26(5):1645–1662. https://doi.org/10.1111/jiec.13245
Lambert C (2024) The politics of circular imaginaries: Exclusion and contestation in Brussels' CE policies. Camb J Reg Econ Soc 17(3):278–297
Lastres HM, Cassiolato JE (2005) Innovation systems and local productive arrangements: new strategies to promote the generation, acquisition and diffusion of knowledge. Innovation: Manage Policy Pract 7(2/3):172–187
Marjanović S, Williams A (2024) Circular economy in shrinking regions: Comparative insights from Finland and the Netherlands. Camb J Reg Econ Soc 17(3):298–317
Marshall A (1920) Principles of economics (8th ed.), Macmillan
Morales ME, Cárdenas S, Gatica S (2019) The circular economy and inclusive development: A research agenda. Ecol Econ 164:106372
Murray A, Skene K, Haynes K (2017) The circular economy: An interdisciplinary exploration of the concept and application in a global context. J Bus Ethics 140(3):369–380
Niang A, Torre A, Bourdin S (2021) Territorial governance and actors' coordination in a local project of anaerobic digestion A social network analysis. Eur Plan Stud 30:7, 1251–1270
Niang A, Torre A, Bourdin S (2022) How do local actors coordinate to implement a successful biogas project? Environ Sci Policy 136:337–347

OECD (2022) Digitalisation for the transition to a resource efficient and circular economy. OECD Publishing. https://doi.org/10.1787/4b6d2f58-en
Paquin RL, Howard-Grenville J (2012) The evolution of facilitated industrial symbiosis. J Ind Ecol 16(1):83–93
Porter ME (2003) The economic performance of regions. Reg Stud 37(6–7):549–578
Rajaonson J, Chembessi A (2024) Local governments and circular economy: Comparative insights from Canadian provinces. Camb J Reg Econ Soc 17(3):407–428
Ravikumar D, Keoleian GA, Walzberg J, Heath G, Heller MC (2024) Resources, Conservation & Recycling Advances Advancing environmental assessment of the circular economy: Challenges and opportunities. Resour Conserv Recycling Adv 21:200203
Reike D, Hekkert MP, Negro SO (2023) Understanding circular economy transitions: the case of circular textiles. Bus Strategy Environ 32(3):1032–1058
Rejeb A, Rejeb K, Zailani S, Kayikci Y, Keogh JG (2023) Examining knowledge diffusion in the circular economy domain: a main path analysis. Circular Econ Sustain 3(1):125–166
Sæther M (2024) Resource loops and spatial mismatch in the circular construction sector: Evidence from Oslo. Camb J Reg Econ Soc 17(3):429–448
Torre A, Gallaud D (eds) (2022) Handbook of proximity relations. Edward Elgar Publishing
Torre A, Rallet A (2005) Proximity and localization. Reg Stud 39(1):47–59
Torre A, Wallet F (2014) Regional development and proximity relations. Edward Elgar, UK
Wasserman S, Faust K (1994) Social network analysis: Methods and applications. Cambridge University Press, Cambridge, UK

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