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RESEARCH

When circular systems scale

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Abstract

Circular economy systems are often designed with a focus on material flows and technological substitution, but their ecological performance is also shaped by geography. As a circular economy expands geographically, it encounters rising institutional diversity, logistical constraints, and behavioral divergence. This paper introduces a framework, based on lessons from the plastics industry, that models how spatial frictions—defined across regulatory, logistical, behavioral, economic, and coordination dimensions—accumulate with scale and undermine system performance. Costs escalate, and reliability deteriorates as circular systems become more spatially dispersed. These dynamics can result in delayed material recovery, inconsistent quality, and increased ecological inefficiency, even when technical feasibility exists. By placing geography at the center of analysis, the paper highlights the need for institutional harmonization, coordination buffers, and spatially adaptive system architectures to sustain circular transitions at scale.

Keywords Circular Economy · Geographical Factors · Spatial frictions · Sustainability · Industrial ecology. · Resource Utilization · Economic Feasibility

JEL Classification Q56 · R12 · O33 · D21 · P48

1 Introduction

The circular economy (CE) promises substantial economic and environmental gains, yet progress remains limited. Estimates by the European Commission suggest that a comprehensive CE transition could yield €600 billion annually in efficiency savings for EU manufacturing, with similar benefits projected for national and global economies (European Commission, 2014; Arponen et al., 2015). Despite these potential gains, implementation has been uneven and slow (Ellen MacArthur Foundation, 2019; Kirchherr et al., 2018). One reason is that geography—long recognized as a determinant of economic outcomes—often remains absent from mainstream CE research. Missions, roadmaps, and strategies are typically presented as if spatially neutral, yet regional science demonstrates that no policy or system is ever neutral with respect to space.

Most studies emphasize technological, market, institutional, or cultural barriers (de Jesus & Mendonça, 2018; Grafström & Aasma, 2021; Kirchherr et al., 2018). These frameworks have advanced our understanding of CE obstacles, but they seldom explore how such barriers evolve with spatial scale. Yet economic geography and spatial economics show that distance, heterogeneity, and institutional fragmentation fundamentally shape performance. Concepts such as spatial transaction costs (Williamson, 1981; McCann, 2001), agglomeration economies (Duranton & Puga, 2004), and regional innovation systems (Cooke, 1992; Asheim & Gertler, 2005) all suggest that geography is not a neutral backdrop but a dynamic force structuring opportunities and constraints.

In particular, the microfoundations of agglomeration—sharing, matching, and learning (Duranton & Puga, 2004)—provide a powerful lens for understanding why circular systems scale unevenly. Sharing refers to access to common specialized infrastructures, matching to efficient allocation of workers, firms, and material streams, and learning to the

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diffusion of knowledge and practices. These mechanisms explain why certain regions excel in innovation and production, but they also highlight why circular systems perform unevenly across space. For example, the benefits of sharing specialized recycling infrastructure, matching waste streams with suitable processors, and learning from localized experimentation are all easier to realize in metropolitan clusters than in peripheral areas. Their absence magnifies frictions when CE systems expand geographically.

The purpose of this paper is to develop a spatially grounded analytical framework that explains how circular systems behave under geographic expansion. Circular economy systems refer to the institutional, material, and logistical arrangements that enable material reuse, recycling, and recovery across economic space. The plastics industry is employed as an illustrative case study in the analysis due to its broad relevance and structural diversity. Several characteristics of plastics—such as quality variability, fragmented infrastructure, and regulatory divergence—also appear in other domains including electronics, construction materials, and textiles (Barford & Åhman, 2021; Bening et al., 2021; Baldassarre et al., 2022). The plastic industry is thus used not only for its internal complexity but for its capacity to illustrate dynamics that apply to other material systems undergoing circular transitions. We argue further that our key aspects of our analytical framework, e.g., those pertaining to institutions, extend to virtually any circular economy.

While existing literature has catalogued numerous barriers to CE implementation—technological, institutional, economic, and cultural—few studies have formalized how such barriers behave with spatial scale. Our contribution is to extend existing frameworks with an explicitly spatial lens, such as the contributions by Kirchherr et al. (2018) and Grafström and Aasma (2021), which identify four broad categories of CE barriers. From this perspective, we distill five recurring frictions: regulatory diversity, logistical constraints, behavioral variation, economic disparity, and coordination difficulty. These five dimensions are not ad hoc: they emerge consistently from systematic and theoretical reviews (Grafström & Aasma, 2021; Kirchherr et al., 2018) and align with concepts in regional science. Coordination is added as a distinct dimension since multi-actor governance challenges intensify with geographic scale. Together, these frictions capture how established CE barriers compound when systems move beyond local or national boundaries.

The contribution of this paper is therefore twofold: (i) to demonstrate how barriers to CE implementation compound with spatial expansion, and (ii) to propose a stylized analytical framework that formalizes these effects through simple modeling. By combining insights from CE studies with foundations in spatial economics, we highlight why geography is central to understanding the limits and possibilities of circular transitions.

2 Four barriers for a CE from a geographical perspective

Before turning to the analytical framework, it is useful to review how geography shapes established barriers to CE implementation. The CE literature commonly distinguishes between technological, institutional/regulatory, economic/market, and cultural barriers (de Jesus & Mendonça, 2018; Grafström & Aasma, 2021; Kirchherr et al., 2018). These categories recur across large-N surveys, systematic reviews, and conceptual analyses. What unites them is that each barrier exhibits strong spatial variation: infrastructures, institutions, markets, and norms differ across places, creating uneven conditions for circular practices. Section 2 therefore synthesizes these established categories with an explicit spatial lens. Section 3 then translates them into five formalized frictions—regulatory, logistical, behavioral, economic, and coordination-related—that can be modeled analytically.

2.1 Economic barriers

Spatial variation in economic conditions introduces frictions to CE systems (Lampinen et al., 2025). Geographical economic barriers include uneven access to materials, imbalances in market size, and cost divergence across regions. In less densely populated areas, smaller volumes of recyclable material reduce the viability of investment in sorting and reprocessing infrastructure (Milios et al., 2018). As a result, several countries with limited domestic capacity export waste to larger, centralized processing hubs, such as Germany, the Netherlands, Belgium, and Italy (Fråne et al., 2015). While integration offers logistical advantages, these benefits are unevenly distributed (Hossain et al., 2022).

These dynamics reflect the classic problem of spatial transaction costs, where thin markets and distance reduce the viability of exchange (Williamson, 1981; McCann, 2001). In agglomerated regions, these costs are offset by dense demand and short supply chains, but in peripheral regions the same transactions become uneconomic. This connects directly to the microfoundations of agglomeration (Duranton & Puga, 2004): in metropolitan regions, firms can share common recycling infrastructure, match waste streams with suitable processors, and learn from localized experimentation. In peripheral regions, these mechanisms weaken—markets are thinner, matching is harder, and learning opportunities scarcer—raising economic frictions for circular practices.

Regional systems may also lack sufficient flows of specific materials—especially those with long lifespans or obsolete compositions—reducing the potential for economically viable recovery. Proximity to suppliers supports quality control and lowers transaction costs, making local sourcing more attractive (Milios et al., 2018). Industrial symbiosis—where firms share materials and infrastructure—relies on spatial closeness and trust, which are often limited to subnational or regional scales (Fraccascia et al., 2019; Oughton et al., 2022).

At certain scales, collection and processing costs exceed market returns (Simon, 2019). Nordic countries exemplify this tension: large territories and dispersed populations raise transport and handling costs, particularly where agglomeration economies are limited (Andersson et al., 2014). Local demand can raise average productivity of the supply side, especially for recycled goods that are costly to transport (cf. Syverson, 2004).

These dynamics can be illustrated by the plastics sector. Virgin plastics are globally traded commodities tied to oil prices, whereas recycled plastics depend heavily on local conditions—collection efficiency, contamination levels, and testing standards (Barford & Åhman, 2021; Baldassarre et al., 2022). This produces volatile and regionally divergent pricing. In some regions, secondary plastic competes successfully with virgin material, while in others price volatility undermines investment incentives. Regional disparities in infrastructure and incentives further distort price signals. Where recovery systems are weak or underfunded, markets for recycled content fail to develop (Tura et al., 2019).

Economic barriers also manifest in financing conditions. High upfront investment costs for recycling infrastructure and circular business models are frequently cited as a deterrent (Rizos et al., 2015; Kirchherr et al., 2018). In smaller or peripheral markets, these costs cannot easily be spread across sufficient material volumes, raising unit costs and risk premiums. Limited access to finance compounds these barriers.

Finally, economic barriers are reinforced by global commodity dynamics. The low price of virgin materials, particularly plastics derived from fossil fuels, makes it difficult for recycled alternatives to compete on cost (Preston, 2012; Mont et al., 2017). Price fluctuations in oil markets are transmitted globally, while recycled material prices remain tied to local infrastructures and demand conditions. This divergence underscores the spatial nature of economic frictions: while virgin material markets are global, circular material markets are often local or regional. The uneven intersection of these scales amplifies cost disparities and disincentivizes investment in circular practices.

2.2 (Formal) institutional and regulatory barriers

Institutions shape what economic actors can achieve with available resources. Even if technological capabilities exist in a region, synthesizing them into products or services may be difficult without institutional support (Neffke & Henning, 2023). Legal frameworks, administrative capacity, and policy priorities differ across jurisdictions, generating friction in cross-regional circular efforts (Veyssière et al., 2022). Circular strategies are often formulated at the national or supranational level but operationalized locally, where interpretations and enforcement vary (Coenen et al., 2015).

Legal inconsistencies intensify as systems expand, complicating cross-border flows and discouraging investment in shared reprocessing. Within the EU, waste directives lack harmonized definitions, creating ambiguity between "waste" and "by-product" classifications (Van Buren et al., 2016). Municipalities play growing roles in collection and recycling, but differences in mandates, funding, and capacity hinder coordination—even within countries (Prendeville et al., 2018; Valentine, 2016). In Italy, for instance, national law prohibits firms from using secondary materials from other firms, limiting industrial symbiosis despite EU encouragement (Taddeo et al., 2017).

At the national level, misalignment between domestic rules and EU directives introduces uncertainty for firms operating transnationally (Shao et al., 2019; Brunnhofer et al., 2020). Legal limits on vertical integration in some countries prevent firms from retaining material control—often a requirement in circular models (Bening et al., 2021). Administrative burdens add further asymmetry: reporting rules, classifications, and enforcement vary across regions, creating uneven compliance costs (de Jesus & Mendonça, 2018; Milios et al., 2019).

Institutions shape what economic actors can achieve with available resources. Even if technological capabilities exist in a region, synthesizing them into products or services may be difficult without institutional support. Legal frameworks, administrative capacity, and policy priorities differ across jurisdictions, generating friction in cross-regional efforts (Neffke & Henning, 2023; Asheim & Gertler, 2005, Cooke & Coenen, 2006). Consider how asymmetries between municipal, national, and supranational mandates hamper effective circular implementation—as when legally viable industrial symbiosis in one region is blocked elsewhere by misaligned rules (Taddeo et al., 2017).

These institutional inconsistencies highlight a core insight from regional science: circular systems are embedded in regional institutional architectures. Regional innovation systems (RIS) theory, for example, emphasizes how local capacity to support innovation depends critically on a broader institutional factors that include regulatory coherence and multi-level coordination (Asheim & Gertler, 2005; Cooke & Coenen, 2006; Andersen & Patel, 2025). In practice, fragmented governance across levels creates transaction costs and uncertainty that are spatially cumulative.

Institutional frictions also interact with other barrier types. Weak enforcement or conflicting standards raise time and compliance costs, effectively discouraging cross-border exchange of secondary materials. Firms forced to navigate inconsistent regulations may abandon market-based reuse strategies in favor of simpler linear models. In contrast, where regulatory alignment exists—such as standardized packaging or harmonized certification—transaction costs fall, trust grows, and firms gain confidence in long-distance circular flows.

Finally, the institutional dimension is central to the politics of scale. Effective circular economy policymaking requires multi-level governance, yet these arrangements often suffer from coordination failures—especially where local, regional, national, and European directives conflict (Valkama et al., 2023; Andersen & Patel, 2025). This reflects long-standing findings in economic geography regarding governance friction: broader ambition does not automatically translate into local effectiveness unless institutional alignment is explicitly designed (European Commission, 2015; Pallemaerts & Azmanova, 2006).

2.3 Technology barriers

Technological barriers are frequently highlighted in the CE literature, often as the primary impediment to circular transitions (Ghisellini et al., 2016; Kirchherr et al., 2018). They include limitations in product design, inadequate infrastructure, insufficient large-scale demonstration projects, and gaps in technical knowledge. Products that are not designed for disassembly, repair, or remanufacturing lock in linear practices, making it difficult to recover value from materials at end of life (Masi et al., 2018). Recycling technologies often lack the capacity to deliver consistent quality, especially when input streams are heterogeneous or contaminated.

Technological barriers are inherently spatial. Infrastructure for collection, sorting, and recycling is unevenly distributed, with some countries or regions operating advanced, integrated systems and others relying on fragmented or outdated facilities (Milios et al., 2018). The result is a geography of uneven technological capacity: while regions such as Germany or the Netherlands have highly developed infrastructures for plastics, others struggle with limited investment and lower technical standards. This unevenness generates friction when material flows cross regional or national borders, as secondary materials collected under one set of technological standards may not meet the quality requirements of another jurisdiction.

The lack of demonstration projects also reinforces spatial disparities. Novel recycling or reuse technologies are typically piloted in metropolitan regions where demand is higher, infrastructures denser, and policy support stronger (Grafström & Aasma, 2021). Peripheral regions, by contrast, often lack the critical mass of actors required to experiment with and diffuse new technologies, reflecting again the agglomeration microfoundations of sharing, matching, and learning (Duranton & Puga, 2004). Demonstration projects depend on shared infrastructure, efficient matching of waste streams with appropriate technologies, and learning through observation and spillovers—all mechanisms that operate more effectively in dense urban clusters than in dispersed rural settings.

Data availability and transparency further constrain technological progress. Companies often lack reliable information on the material composition of products, the environmental impacts of different recycling methods, or the performance of secondary materials (Pheifer, 2017). These informational gaps have spatial dimensions as well: data-sharing platforms and digital product passports are more commonly adopted in technologically advanced regions with stronger institutional coordination, leaving lagging regions without comparable knowledge infrastructures.

Finally, technological barriers interact with other categories of barriers. For example, fragmented institutional frameworks impede cross-border deployment of new technologies, while weak consumer demand for recycled products discourages firms from investing in advanced processing capacity. In this sense, technological barriers should not be viewed as isolated obstacles but as regionally embedded frictions whose severity depends on spatial context. In agglomerated regions, technological barriers may be partly offset by scale and density advantages, while in peripheral regions the same barriers can become binding constraints.

2.4 Cultural and behavioral barriers

Social Cultural and behavioral barriers are increasingly recognized as central to the CE transition. While earlier studies emphasized technological or market failures, large-scale surveys and reviews show that cultural factors—such as consumer preferences, company culture, and willingness to collaborate—are often decisive (de Jesus & Mendonça, 2018; Kirchherr et al., 2018). Hesitant company cultures, limited consumer awareness, and entrenched linear habits have repeatedly been identified as among the most pressing barriers in European contexts.

Consumer behavior is a recurring constraint. Many consumers lack awareness of circular alternatives or perceive them as lower quality, less convenient, or more expensive (Mont et al., 2017). Even where awareness exists, purchasing decisions often remain driven by cost, leading to continued preference for cheap, virgin-based products over recycled alternatives (Ranta et al., 2017). This consumer hesitancy is spatially uneven: in some regions, high levels of environmental awareness and social norms encourage adoption of reuse and recycling schemes, while in others, weak environmental cultures and limited exposure to circular practices slow uptake. Cultural preferences thus map unevenly across space, amplifying geographic differences in CE outcomes.

Corporate culture presents another major barrier. Surveys show that even firms with sustainability strategies often confine CE initiatives to CSR or environmental departments, rather than integrating them into core operations such as procurement, logistics, or product design (Pheifer, 2017). This fragmentation reflects the difficulty of embedding new routines within established production systems, which vary across regions. Firms in agglomerated clusters may be more exposed to peer effects and learning-by-observation, accelerating adoption of circular practices, while firms in more peripheral contexts may lack such networks and remain locked into linear models.

Collaboration across value chains is also a persistent challenge. CE models often require coordination between multiple firms, sectors, and consumers. Yet cultural reluctance to share data, adapt processes, or establish long-term partnerships frequently impedes collaboration (Mont et al., 2017). Here again, spatial dynamics matter. Dense regional clusters can facilitate trust and repeated interaction, lowering cultural barriers to collaboration, while dispersed or fragmented regions face higher coordination costs and greater reluctance to cooperate.

Cultural barriers also interact with institutional and economic frictions. For example, weak consumer demand for secondary materials discourages investment in advanced recycling technologies, while hesitant company cultures reduce political pressure for regulatory harmonization. Conversely, strong cultural norms in favor of sustainability—as seen in certain Nordic countries—can push policymakers to adopt stricter standards and create new markets for recycled products. This mutual reinforcement highlights that cultural and behavioral barriers are not isolated, but embedded within broader regional dynamics.

In summary, cultural and behavioral factors—consumer attitudes, company cultures, and collaboration norms—represent some of the most decisive barriers to CE. They are also spatially uneven: some regions exhibit strong pro-circular cultures that accelerate transition, while others remain locked in linear habits. Recognizing these differences is essential, since the effectiveness of circular policies often depends less on technical feasibility than on cultural receptivity and behavioral change at the regional scale.

2.5 Summary of barriers and their spatial context

The barriers reviewed above—economic, institutional/regulatory, technological, and cultural/behavioral—are well-established in the circular economy literature (de Jesus & Mendonça, 2018; Grafström & Aasma, 2021; Kirchherr et al., 2018). They describe the many ways in which circular practices are constrained across different places and scales. Yet while these categories capture the diversity of obstacles, they are not directly suited for analytical modeling. Several challenges arise.

First, the categories overlap substantially. For instance, economic and technological barriers are often intertwined: transport costs depend on available infrastructure, and product design interacts with market incentives. Similarly, institutional and cultural barriers are mutually reinforcing: divergent regulations shape consumer confidence, while behavioral norms influence regulatory implementation. Modeling each barrier category separately risks duplication, collinearity, and loss of tractability.

Second, the categories are highly heterogeneous. “Economic barriers” can refer to everything from the volatility of plastic prices to the absence of industrial symbiosis opportunities, while “technological barriers” span issues as different as product design, recycling quality, and testing standards. Without simplification, it is difficult to translate these diverse issues into measurable dimensions that can be simulated.

Third, the categories are largely descriptive. They catalogue what has been observed in empirical studies but do not readily translate into the kind of stylized variables that allow us to explore system dynamics under different spatial scenarios. To move from description to analysis, we need to extract cross-cutting mechanisms that capture how these barriers accumulate and interact when systems scale.

For this reason, we condense the barriers into five stylized frictions—regulatory, logistical, behavioral, economic, and coordination-related—that can be explicitly modeled. Each friction is anchored in the barriers presented in Sect. 2 but reformulated to capture a specific mechanism of spatial scaling. Regulatory frictions capture divergence in laws and standards (linking back to Sect. 2.2). Logistical frictions reflect transport and infrastructure constraints (arising from both economic and technological barriers, 2.1 and 2.3). Behavioral frictions represent spatial variation in consumer and firm practices (Sect. 2.4). Economic frictions capture cost disparities and market thinness (Sect. 2.1). Finally, coordination frictions are introduced as a distinct category to address multi-actor governance challenges that cut across all four barrier types but intensify systematically with scale.

This translation is not a one-to-one mapping of barriers into model parameters, but rather a distillation of the underlying dynamics most relevant to spatial expansion. It allows us to retain the richness of the literature review while creating a tractable framework for analysis. In doing so, we respond to calls for conceptual clarity in CE research (Korhonen et al., 2018; Kalmykova et al., 2018) and explicitly ground our modeling choices in established theoretical traditions from economic geography and spatial economics.

Table 1 Typology of spatial frictions across spatial scales

Friction Type	Local Context	Regional Context	Cross-border Context	System-level Implications
Economic	Small market size; high per-unit costs. Positive: localized demand can sustain niche recovery markets	Cost divergence; infrastructure gaps. Positive: clustering generates scale economies and efficiencies	Trade friction; scale mismatch; input mismatch. Positive: larger markets expand material availability and specialization	Volatile pricing, underutilization, inefficient allocation. Positive: agglomeration reduces costs through sharing, matching, learning
Institutional	Local mandates; fragmented governance. Positive: municipalities can pioneer innovative CE schemes	Policy divergence; overlapping jurisdictions. Positive: regional alignment can harmonize incentives and reduce barriers	Legal fragmentation; compliance asymmetry. Positive: supranational harmonization creates stable, predictable markets	High admin burden; low policy coherence. Positive: coherent rules enhance trust, reduce risk, and attract investment
Technological	Infrastructure gaps; low specialization. Positive: experimentation possible at small scale	Limited interoperability; regional tech divides. Positive: regional hubs can concentrate R&D and spillovers	Standard incompatibility; fragmented certification regimes. Positive: cross-border standards enable scaling and quality assurance	Interruption of loops; downcycling; process bottlenecks. Positive: technology harmonization raises efficiency and quality
Behavioral (Social)	Low engagement; awareness gaps. Positive: community-level initiatives can mobilize rapid change	Trust and coordination barriers. Positive: social capital within clusters fosters collaboration	Divergent norms; safety perceptions. Positive: cultural exchange can diffuse best practices across borders	Participation risk; quality variability. Positive: strong demand signals from consumers/companies drive adoption
Coordination (extension)	Informal routines; personal networks. Positive: flexibility and trust-based collaboration at small scales	Increased number of actors and interfaces. Positive: regional cluster organizations can lower coordination costs	Institutional misalignment; lack of synchrony. Positive: international platforms enable standardization and planning	Reliability erosion; planning uncertainty. Positive: robust coordination mechanisms improve resilience

The main features of each friction across local, regional, and cross-border contexts are summarized in Table 1.

This dual perspective is important. Previous studies (Grafström & Aasma, 2021; Kirchherr et al., 2018) have generally emphasized the negative side of these barriers, but our framework highlights that they also contain enabling dynamics. The same factors that hinder scaling under some conditions may foster resilience and innovation under others. By integrating both barriers and positive aspects, we acknowledge the possibility of non-linear effects: thresholds, turning points, and feedback loops that alter how frictions play out across space.

The next step is to formalize these insights into a tractable analytical framework. Section 3 translates the five categories of barriers into five stylized spatial frictions—regulatory, logistical, behavioral, economic, and coordination-related—that can be systematically modeled. This translation allows us to move from descriptive accounts of barriers toward a simplified, yet theoretically grounded, representation of how geography shapes circular economy outcomes.

To further illustrate how the five friction types manifest in practice, Table 2 presents concrete cases drawn from the literature. Each example provides a short narrative of how economic, institutional, technological, behavioral, and coordination frictions emerge in real contexts.

3 Method and analytical framework

The starting point is an investigation of CE research with attention to how barriers to implementation vary across geographical contexts. Rather than proposing a new typology, the analysis builds on established frameworks that classify barriers as technological, institutional, market-related, or cultural (Kirchherr et al., 2018; de Jesus & Mendonça, 2018; Grafström and Aasma, 2023). The goal was to reinterpret these categories through a spatial lens. Through thematic coding of the reviewed literature, five recurring dimensions of spatial friction were identified:

- Regulatory diversity (R): legal definitions, enforcement capacity, and jurisdictional overlap complicate material flows.
- Logistical constraints (L): transport costs and infrastructure quality affect collection, processing, and redistribution.
- Behavioral variation (B): public engagement, firm-level norms, and trust conditions vary across space.
- Economic disparity (E): resource availability, labor costs, and infrastructure investment differ regionally.

Table 2 Concrete illustrative cases of spatial frictions, based on the literature

Friction type	Illustrative case	Description
Economic	Plastics recycling in the Nordic countries	A recycling truck travelling long distances between scattered villages collects only small volumes of plastic, making each trip costly. Processing plants stand half-empty because material inflows are thin, and the recycled output struggles to compete with cheaper virgin plastics
Institutional / Regulatory	Industrial symbiosis in Italy	A company with leftover material from production seeks a nearby partner who could reuse it, yet national law prohibits such exchange. Even though EU rules encourage cooperation, local firms are forced to discard material that could have been recovered, turning opportunity into waste
Technological	Plastics infrastructure in Northern vs. Central Europe	In the Netherlands, modern automated sorting lines separate plastics with high precision, producing clean and reliable output. A few hundred kilometers away, smaller facilities in peripheral regions rely on outdated equipment, generating mixed streams that cannot meet industrial standards
Behavioral	Consumer preferences in plastics markets	Shoppers entering a store see two similar products: one made from virgin plastic at a lower price, the other from recycled content but slightly more expensive. Many choose the cheaper option, reinforcing habits that slow demand for secondary materials, even in regions with high awareness of sustainability
Coordination	Municipal recycling authorities in England and Sweden	A producer of packaging aims to design a nationwide recycling scheme but faces hundreds of different local rules. In England alone, 317 authorities demand separate reporting formats, and in Sweden 290 municipalities apply their own collection systems. What looks simple on paper becomes a maze of procedures

- Collaboration difficulty (*Co*): institutional alignment, political will, and information flows often decline as systems span more territories.

Thematic coding was organized in three fundamental steps. All barrier categories reviewed in Sect. 2 were broken down into discrete statements, producing a set of observations on how geography shapes CE implementation. Each statement was coded according to how we perceive its underlying mechanism, such as legal divergence, infrastructure capacity, consumer behavior, market size, or governance alignment. Codes were clustered into broader categories based on recurrence across sources and conceptual similarity. This process yielded five dimensions of spatial friction: regulatory diversity (R), logistical constraints (L), behavioral variation (B), economic disparity (E), and coordination difficulty (Co).

A strength of the coding process is that it allowed us to condense a wide and sometimes fragmented literature into a set of recurring mechanisms that can be analyzed. At the same time, the process is far from free from subjectivity. Certain barriers could reasonably have been assigned to more than one category, and the boundary between economic and technological issues, for instance, was sometimes difficult to draw. The taxonomy is not perfect but works operationally. Alternative coding decisions might have produced slightly different groupings, yet we believe the five frictions identified here capture the most salient dynamics.

These five dimensions serve as inputs into the analytical framework. The identified friction types were translated into a stylized conceptual model of system performance. The model draws on microeconomic logic and systems theory (Varian, 1992; Choi et al., 2001; Acemoglu, 2008) to describe how friction intensifies with spatial scale. It assumes that performance does not degrade uniformly, but that coordination cost, sourcing reliability, and timing risk grow disproportionately as systems expand.

A set of interrelated equations links the number of jurisdictions or collection points (*n*) to indicators of complexity, cost, and fragility. The model uses additive and multiplicative forms to represent friction types of compounds at larger scales. Complexity is modeled as a function of scale and friction values, and sourcing cost incorporates both material costs and transaction costs associated with coordination.

Rather than aiming for parameter precision or empirical estimation, the goal is to formalize interactions between friction types. The model structure is designed to surface structural risks: the ways in which systems may become less efficient or more vulnerable not because of material input issues, but due to misalignment in institutions, timing, and expectations across region.

Simulations were used to explore how spatial friction alters circular system behavior. A range of stylized scenarios were constructed by assigning plausible values to the friction variables at different levels of geographic scale (e.g., local, regional, cross-border). Each simulation tracks changes in key outcomes as spatial scale increases: total sourcing cost, system complexity, coordination burden, supply reliability, and timing mismatch. The simulations begin with relatively low values of friction and scale up across jurisdictions, allowing the interaction effects to emerge. The objective is not to replicate any specific real-world case, but to identify patterns of nonlinear cost accumulation and reliability breakdown as spatial dispersion increases.

The simulation logic, key assumptions, and outcome measures are summarized in Table 3. The results presented in Sect. 4 are used to reflect on how circular systems perform under spatial pressure, and to identify design considerations for systems operating beyond the local scale.

Table 3 Overview of methodological steps for identifying and modeling spatial frictions

Stage	Description	Output
1. Literature review	Identification of CE barriers and spatial variation across academic sources	Thematic map of friction types
2. Friction synthesis	Coding of geographic dimensions: regulation, logistics, behavior, economics, coordination	Five friction dimensions (*R, L, B, E, Co*)
3. Model construction	Translation of frictions into variables and system-level relationships using stylized equations	Conceptual model of spatial friction and complexity
4. Simulation design	Assignment of hypothetical values to friction types and spatial scales	Equations (1) – (10) linking geography to CE outcomes. Friction-based scenario space (e.g., 3, 6, 9 regions)
5. Simulation execution	Iterative testing of system outcomes under increasing scale and compounded friction	Output trajectories for cost, complexity, and reliability
6. Interpretation and framing	Evaluation of nonlinear effects; implications for circular design and policy	Analytical framework for spatial constraints in CE systems

4 Spatial complexity in circular systems.

4.1 Conceptual model: geography and system friction

To formalize how spatial scale interacts with circular system performance a three-layer analytical framework is introduced: spatial scaling, friction channels, and stylized equations. Five friction channels link spatial variation to circular outcomes are used (R, L, B, E, Co) and were introduced in Sect. 3.1. Each of these frictions can be linked to spatial scale. At the local level, systems benefit from proximity, coherence, and trust. As scale increases—moving from municipal to regional and cross-border systems—divergence increases across all five dimensions.

Geographical complexity increases as CE initiatives move from local to regional and cross-border scales. At the local level, spatial proximity, administrative coherence, and social familiarity tend to reduce coordination costs. As CE systems span multiple jurisdictions, variations in infrastructure quality, institutional capacity, and regulatory frameworks introduce divergence. At the cross-border level, fragmentation in legislation, logistical infrastructure, and market conditions create additional coordination challenges. Spatial scale thus serves as a proxy for institutional and infrastructural heterogeneity.

To capture the effect of increasing scale two expressions of system complexity are introduced. The first defines complexity as a function of the number of spatial units involved:

$$C = f(n) \tag{1}$$

Equation (1) reflects the basic insight from systems theory: as more independent actors are added, coordination becomes harder (Choi et al., 2001) As n grows, C increases. Equation (2) makes this more explicit:

$$C = f(n, R, L, B, E, Co) \tag{2}$$

where, as a reminder, C represents the overall complexity of the circular system, n is the number of locals involved, R captures regulatory diversity, L reflects logistical constraints, B accounts for behavioral variation, E represents economic disparity, and Co denotes coordination difficulty. This structure allows for formal modeling of how friction scales. As systems expand geographically, C increases linearly if friction remains stable. But when divergence increases with scale—as often occurs with L and Co—C rises nonlinearly. The conceptual framework connects qualitative insights from literature to a stylized modeling structure that can be explored through simulation.

We simulate how overall complexity grows with scale using Eq. (2). The following values represent a system operating across three moderately divergent regions:

- $R = 2$ (moderate variation in waste legislation)
- $L = 3$ (moderate logistical challenges)
- $B = 2$ (differences in consumer and institutional behavior)
- $E = 2$ (variation in infrastructure, input prices, and market size)
- $Co = 3$ (coordination challenges due to different political or administrative systems)

The values R = 2, L = 3, B = 2, E = 2, and Co = 3 are grounded in recurring findings in the reviewed literature: regulatory divergence is often noted as a persistent but moderate barrier; logistical and coordination challenges are repeatedly described as more substantial, particularly in cross-border contexts; and behavioral as well as economic barriers are reported as important but generally moderate in comparison. The scale is therefore designed to reflect relative weight across frictions rather than exact measurement.

Applying Eq. (2): $C = n \times (R + L + B + E + Co)$ yields the complexity outcomes in Table 3 (the factors themselves can also scale, but for simplicity they have not been developed). This simple formulation illustrates a central point: geographical expansion multiplies—not adds—complexity, and even modest increases in heterogeneity generate nonlinear system burdens. Even when average friction values stay constant, complexity scales linearly. If frictions rise with n, total complexity increases more steeply.

The following section applies the model using hypothetical values to demonstrate how spatial frictions generate cost asymmetries and performance degradation in circular systems.

4.2 Demonstration – scaling complexity and cost in a stylized CE system

To illustrate how spatial scale influences system behavior, this section applies the framework developed in Sect. 4.1 to a series of stylized simulations. The goal is not to predict real-world values, but to demonstrate how increases in regional coverage and friction generate compounding effects in system complexity and cost. The first step is to link structural complexity to sourcing cost. Equation (3) expresses the cost of sourcing virgin and circulated materials:

$$\begin{aligned} C_{VM} &= C_{purchase} + C_{transport} + C_{processing} < C_{RM} \\ &= \sum_{i=1}^{n} C_{purchase_i} + C_{transport_i} + C_{processing_i} \end{aligned} \tag{3}$$

In Eq. (3), n is the number of collection points. The second expression shows how circulated material sourcing involves disaggregated costs across n sites. A manufacturer sourcing virgin inputs from global markets may rely on a single delivery point, simplifying logistics. Global commodities offer price certainty and supply flexibility, enabling easier adjustment to shocks (Martinez-Sanchez et al., 2015; Miah et al., 2017; Rieckhof & Guenther, 2018).

To account for unpredictability and coordination burden in circulated sourcing, Eq. (4) is introduced:

$$C_{CM} = \sum_{i=1}^{n} C_{purchase_i} + C_{transport_i} + C_{processing_i} + T_{Ci} \tag{4}$$

Here, TC_i, encapsulates the transaction costs such as negotiations, contracting, monitoring, and managing the uncertainties related to the timing and availability of circulated materials at each collection point i (Table 4).

Equation (4) is now applied to estimate total costs of sourcing circulated materials (CCM) from a decentralized network of collection points (Table 5). Assume three collection points ($n = 3$) with the following values (in arbitrary units) Now consider an expansion to $n = 6$, adding three more collection points with similar characteristics but slightly higher transaction costs due to regional complexity:

Although costs at each site do not change drastically, coordination costs rise, pushing total sourcing costs higher than a linear scaling would suggest. Transaction costs are sensitive to institutional heterogeneity, regulatory incompatibility, and uncertainty in delivery or quality. The simulation demonstrates two interrelated consequences of geographic scaling: rising system complexity and accelerating cost growth.

Figure 1 visualizes the relationship between geographic scale and two key performance metrics in circular systems: system complexity and sourcing cost for circulated materials. The solid line represents linear complexity growth under constant average frictions. The dashed curve shows how complexity escalates more steeply when frictions increase with scale—a typical pattern in cross-regional or cross-border systems. Overlaid on these complexity curves is the cost trajectory derived from the sourcing cost simulations in Table 4.

The figure makes clear that spatial expansion introduces compounding effects: not only do system coordination demand grow faster than the number of collection points, but sourcing costs for circulated inputs also accelerate due to administrative and quality-management burdens. These effects are not captured by conventional cost models that assume uniform sourcing environments.

Table 4 Complexity growth with regional expansion and rising friction

Number of Regions *(n)*	Friction Sum $(R+L+B+E+Co)$	Total Complexity $(C = n \times sum)$
3	12	36
6	12	72
9	12	108
9 (with higher frictions)	14	126

Table 5 Sourcing cost for circulated materials, 1–6 collection points

i	$C_{purchase_i}$	$C_{transport_i}$	$C_{process_i}$	TC_i	Total
1	10	12	8	5	35
2	9	10	7	6	32
3	11	11	9	5	36
4	10	13	9	7	39
5	12	14	10	8	44
6	11	12	9	7	39
			CCM (points 1–3) = 103	Total CCM (points 4–6) = 122	Total CCM ($n = 6$) = 225

4.3 Coordination cost and reliability breakdown in dispersed systems

To isolate the effect of coordination costs, a stylized circular system simulated composed of six collection points. Material, transport, and processing costs are fixed across sites, while the transaction cost per site (TC_i)—representing administrative overhead, legal compliance, and coordination effort—is varied. The base values used in the simulation are $C_{purchasei} = 10$, $C_{transporti} = 12$ and $C_{processi} = 9$, Baseline $T_{Ci} = 5$, with all sites assumed to operate under identical technical conditions. Assume a CE system with $n = 6$ collection points. Material, transport, and processing costs are held constant, while TC_i — reflecting administrative, contractual, and regulatory coordination — varies across scenarios. The baseline cost per collection point is: $CCM_i = 10 + 12 + 9 + TC_i = 31 + TC_i$. Then TC_i is incrementally increase from 2 to 10 units and observe the resulting changes in total sourcing cost across the six-point system. The outcomes, summarized

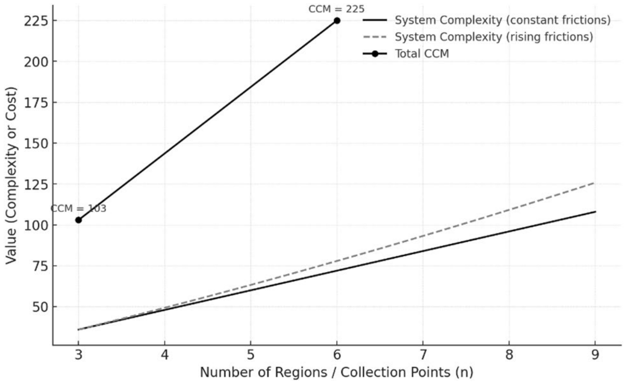

Fig. 1 System complexity and circulated material sourcing cost (CCM) as a function of the number of regions or collection points (n). Underlying data for Fig. 1 are available in Table 4 and 5

in Table 6, show how small increases in coordination costs can produce noticeable system-wide effects.

An increase in TCᵢ from 5 to 8 units—representing a relatively modest rise in administrative friction—raises the total cost by 18 units, or approximately 14 percent. This shift occurs without any change to logistics, input prices, or infrastructure. To approximate this burden in spatial terms, we introduce a system-level coordination cost function:

$$C_{RM} = n \times (D_{avg} + P_{avg}) \tag{5}$$

Here, n is the number of collection points, D_{avd} the average distance to the processing center, and P_{avd} the average number of processing steps (things needed to be done). As each factor increases, so does operational complexity. The formula builds on insights from network theory and systems dynamics (Pathak et al., 2007; Rebs et al., 2019).

Municipalities often manage initial collection, but jurisdictional fragmentation limits integration. England, for instance, has 317 local authorities; Sweden has 290 (11 of which had fewer than 4,000 inhabitants in 2023). Each applies distinct rules and capabilities. The result is hundreds of possible interfaces for producers who aim to build cohesive supply chains.

In linear supply chains, firms rarely reclaim used products directly. Many are not licensed to handle waste and cannot retrieve materials even when consumers are willing (Sthiannopkao & Wong, 2013). Specialized recyclers usually perform collection and reprocessing, selling inputs back to manufacturers. This arrangement fragments responsibility and limits traceability.

In addition to direct costs, coordination failure carries risk. Equation (6) introduces this broader penalty structure:

$$TC_{CM} = T_{coordination} + \sum_{i=1}^{n} T_{C_i} + SIF_{CM} \times Penalty_{supply} \tag{6}$$

Table 6 Total sourcing cost under increasing transaction costs

TC_i (per point)	CCMᵢ	Total CCM (n = 6)
2	33	198
3	34	204
4	35	210
5 (baseline)	36	216
6	37	222
7	38	228
8	39	234
9	40	240
10	41	246

where $T_{coordination}$ represents the overhead of managing a dispersed network, and $Penalty_{supply}$ quantifies the cost of missed deliveries, rejections, or low-quality batches. These costs add a layer of complexity beyond logistics and highlight the role of uncertainty in shaping CE outcomes. The unpredictability of circulated material availability (SIF_{CM}) and fluctuations in the demand for circulated or reused products (DIF_{CP}) add layers of complexity to the supply chain, influencing both logistical arrangements and cost efficiency.

Different geographical regions can exhibit varying levels of supply chain reliability. Some areas may have more dependable and resilient supply chains for both virgin and circulated materials, while others may face challenges that lead to inconsistency and unpredictability (Lampinen et al., 2025). In the realm of material supply chains, reliability is a critical factor that impacts the efficiency and effectiveness of operations. To evaluate and compare the reliability of sourcing virgin materials (R_{VM}) and circulated materials (R_{CM}), a quantitative measure known as a reliability score can be utilized:

$$\begin{aligned} R_{VM} &= \frac{1}{Variability_{supplier} + Delay_{risk}} \, and \, R_{CM} \\ &= \frac{1}{n \times Variability_{collection} + Delay_{risk-total}} \end{aligned} \tag{7}$$

Here, $Variability_{suppliers}$ refer to fluctuations in material quality and timing for virgin inputs; $Variability_{collection}$ captures inconsistencies in the flow of circulated materials. $Delay_{risk}$ and $Delay_{risk\text{-}total}$ represent disruption risks. Higher reliability scores reflect more stable, predictable flows.

Equation (8) and (9) consider supply inconsistency, handling supply of circulated materials from various collection points and incorporate temporal elements, respectively. The methodology is informed by stochastic modeling, which is commonly used in supply chain analysis to predict the reliability of supply given variability and time-dependent factors (Karthick, 2024; Mallick et al., 2018).

For circulated materials, both variability and delay risk tend to increase with distance due to decentralized collection networks, inconsistent quality, and heterogeneous transport and regulatory conditions. Virgin material supply chains, by contrast, are often centralized and standardized, benefiting from more robust infrastructure and streamlined logistics.

The simulation emphasizes a core point: CE systems are spatially fragile. Beyond a certain scale, the advantage of proximity becomes critical—not just for reducing cost (as shown in Sect. 4.2), but for maintaining dependable material flows. Proximity enables better coordination, more accurate sorting and quality control, and faster adaptation to fluctuations in input availability.

The supply inconsistency factor for circulated material (SIF_{CM}) is a quantitative measure that assesses the degree of inconsistency or variability in the availability of recyclable materials at various collection points within the circulated material supply chain:

$$SIF_{CM} = \frac{1}{n}\sum_{i=1}^{n} Variability_{supply_i} \tag{8}$$

Here, $\text{Variability}_{\text{supply}_i}$ represents the fluctuation in availability at each collection point i, and n is the total number of collection points. As n increases, so does the potential for divergence in input quality, timing, and volume. In a stylized comparison, two systems with six collection points yield different SIF_{CM} values based on their variability profiles (Table 7):

As shown, fragmented systems introduce more than double the inconsistency burden. Variability in collection accuracy, reporting, and participation undermines system performance and increases the need for costly buffering and sorting. We extend the model by incorporating timing uncertainty using Eq. (9):

$$TSIF_{CM} = \frac{1}{n}\sum_{i=1}^{n} Variability_{supply_i} + Time_{supplyi} \tag{9}$$

where $TSIF_{CM}$ represents the Time-Adjusted Supply Inconsistency Factor for Circulated Material. It quantifies both the variability and time-related aspects of supply inconsistency within the circulated material supply chain. $Time_{supply_i}$ reflects delays or misalignments between availability and processing needs—such as seasonal fluctuations or delivery gaps. These distortions compound as the number of collection points increases and synchronization becomes harder.

The significant increase in $TSIF_{CM}$ between the two cases demonstrates how even moderate delays can amplify inconsistency, particularly in systems with limited flexibility or buffering capacity.

Beyond supply-side variability, the demand side also varies across space and time. Consumption patterns are shaped by product type, geography, and timing. Certain materials—such as flooring or structural plastics—remain in place for decades. Others follow seasonal or cyclical trends (Gowrisankaran & Rysman, 2012; Hastings & Washington, 2010). Demand inconsistency can be modeled using a simple variance-based metric:

$$DIF_{CP} = \sigma_{demand} \tag{10}$$

where σ^2_{demand} values indicate markets where demand is volatile or unpredictable, making it difficult to synchronize input recovery with production needs. This is particularly problematic in systems that lack stockpiling capacity or operate under strict "just-in-time" processing constraints. Regulatory limits on storing waste materials further reduce flexibility, making circular systems more sensitive to temporal demand fluctuations. Certain materials are regionally constrained. For example, input streams for recycling may depend on local industrial profiles or historical consumption. This limits the feasibility of uniform CE systems across regions.

Table 7 Supply inconsistency in harmonized and fragmented systems and time-adjusted supply inconsistency under delay scenarios

System type	Variability values	Total variability	SIF_{CM}
Harmonized	[3, 3, 4, 3, 4, 3]	20	3.3
Fragmented	[6, 8, 9, 7, 6, 9]	45	7.5
Mismatch type	Delay values (days)	Avg. delay	$TSIF_{CM}$
Low mismatch	[1, 2, 1, 2, 1, 1]	1.3	≈ 4.3
High mismatch	[5, 6, 4, 6, 5, 7]	5.5	≈ 41.3

5 Discussion

The simulations presented in Sect. 4 reveal that, under our assumptions, circular systems face coordination costs and reliability risks that grow disproportionately with spatial expansion. The more jurisdictions involved, the more likely it is that regulatory definitions, behavioral norms, and infrastructural capabilities will diverge. Spatial expansion creates friction that undermines predictability and drives up sourcing costs—even when basic infrastructure is in place.

The numbers tell a clear story. When a circular system operates across three regions, total sourcing cost for circulated materials lands at 103 units. Add just three more collection points—keeping material, transport, and processing costs stable—and the total jumps to 225 (Table 4). The culprit isn't the physical flow of goods, but the growing coordination burden embedded in each added jurisdiction. Table 4 sharpens the point: with moderate frictions, system complexity scales linearly; with increasing frictions, it rises steeply. For firms trying to build region-spanning circular supply chains, this means each step outward multiplies risk, not just effort.

Cost is not the only constraint—reliability starts to break down too. When coordination costs rise incrementally from 5 to 8 units per site, total system cost grows by 14 percent without touching a single truckload of material (Table 5). In parallel, reliability collapses. In a fragmented system, the supply inconsistency factor more than doubles compared to a harmonized setup (Table 6).

For industry and policymakers, the lesson is hard to ignore: scaling circularity is not just a matter of replicating what worked locally. When systems cross administrative, behavioral, and infrastructural boundaries, frictions compound—quietly at first, then decisively. Firms looking to grow reuse or recycling networks across regions need more than clean tech and carbon accounting—they need synchronization protocols, trust-building mechanisms, and region-specific coordination tools. Infrastructure matters, but institutional choreography matters more. Without it, circular ambition risks becoming linear frustration—just spread out over more territory.

A big-small paradox exists here. For circular systems to make a substantial difference, they need to be large in scale, to encompass sufficient capabilities and materials. At the same time, the smaller they are, the easier they are to coordinate in terms of knowledge of time and place, quality and so on. For our circular systems to be of sufficient size, this management is key, and it seems economic geographers have not spent sufficient time and effort on this topic.

A main point in this paper is the complexity that arises when applying a regional, spatial, and geographical lens to CE issues. The logistics chain responsible for collecting and redistributing used materials must be well-prepared to handle variations accommodating temporal fluctuations in demand and variations in material quality. Materials retrieved for circulation may not always conform to production standards, and logistics providers need to be adaptable to process such materials effectively (Haas et al., 2015).

The scope of a market is not necessarily global. Numerous heavy commodities are traded at varying prices worldwide, and opportunities for arbitrage, particularly in importing them, are often non-existent (Wårell, 2014). Consequently, the extent of a circular market within Europe remains uncertain, as does the potential emergence of distinct clusters of regions or countries that firms may rely on for sourcing materials.

Can the results have policy implications? Yes, the simulations point to several targeted interventions, maybe not fit for all countries but some. First, since it seems like coordination costs rise disproportionately with scale, governments could establish regional/national/multinational clearinghouses or digital platforms to standardize contracts, reporting, and certification. Such measures may lower the transaction costs highlighted in Table 5, yet they also require upfront investment and risk creating additional administrative routines if adoption is uneven or they are better for a specific country. Second, to address reliability breakdowns, policymakers could introduce buffer capacities such as regional stockpiles of recycled material or flexible procurement quotas that absorb variability in supply. If this procurement is politically accepted it is another issue, but at the present time there seems to be a larger willingness to accept strategic stockpiles and national autonomy. At the same time, stockpiling ties up capital and storage space, and procurement quotas may distort markets if demand signals are weak. Third, because sourcing costs increase with distance, transport subsidies or investments in decentralized reprocessing hubs could offset logistical frictions. A counterpoint is that subsidies can create fiscal commitments over the long term, and decentralized facilities may lack economies of scale, making them costly to operate if material flows are insufficient.

6 Concluding remarks and directions for future research

This paper has argued that circular economy systems cannot be understood without attention to geography. Building on established CE barrier frameworks (Grafström & Aasma, 2021; Kirchherr et al., 2018), we developed a spatially grounded perspective that reinterprets these barriers as five recurring frictions: regulatory diversity, logistical constraints, behavioral variation, economic disparity, and coordination difficulty. By situating these frictions within traditions of spatial economics—transaction cost theory, agglomeration economies, and regional innovation systems—we provide a conceptual bridge between the CE literature and economic geography.

Our analysis shows that circular systems which function well in local contexts often struggle to scale regionally or across borders. Local proximity enables trust, informal coordination, and lower logistics costs, but as systems expand, divergence in infrastructures, standards, and cultural norms becomes more salient. Cross-border systems may deliver economies of scale and risk diversification, yet only if regulatory and infrastructural harmonization mechanisms are in place. Geography therefore operates not as a backdrop but as an active determinant of system performance.

While our examples draw primarily from plastics, the framework is not confined to that sector. Similar frictions can be observed in construction materials, electronics, and textiles, where heterogeneous infrastructures and regulatory fragmentation shape outcomes. By contrast, metals illustrate a lower-friction case, underscoring the importance of sectoral specificity in applying the framework. These illustrations provide empirical grounding, but we acknowledge that full validation requires dedicated, comparative studies.

For policy, the findings highlight the limits of spatially neutral CE strategies. Effective interventions must be place-sensitive: at the local scale, fostering trust-based networks and small-scale infrastructures; at the regional scale, supporting interoperability and institutional alignment; and at the cross-border scale, investing in harmonized standards, modular infrastructures, and governance platforms. In short, CE policy must be designed not only around material flows but around the geographies through which those flows circulate.

A methodological limitation of our study is that the model parameters are stylized and intended to illustrate dynamics rather than quantify outcomes in specific contexts. The framework shows structural risks associated with spatial expansion, but empirical validation is likely required to confirm the scale and magnitude of these effects. Comparative country level case studies and sector-specific data could be used to calibrate the parameters more precisely and test the robustness of the model across jurisdictions.

Future research should build on this conceptual framework by quantifying how frictions evolve with distance, density, and institutional diversity. Empirical work could test alternative functional forms, explore nonlinearities, and identify thresholds where frictions become binding. By bringing spatial economics into dialogue with CE research, we provide a foundation for such inquiry.

In sum, this paper advances the CE debate by demonstrating that barriers are not context-free, but structured by geography. Recognizing their spatial dynamics allows scholars to move beyond static typologies, and enables policymakers to design strategies that are both circular and place-sensitive.

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