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How does space matter? On the importance of embedding spatialities in industrial ecology frameworks for circularity in the built environment

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Abstract

This paper explores the critical role of spatiality and scale in industrial ecology (IE) research to promote circularity within the built environment. Traditional IE frameworks are predominantly a-spatial and a-political, overlooking the complex socio-ecological–technological dynamics of urban–regional environments. This gap limits the development of holistic assessments and effective strategies for circularity, often externalizing political, economic, and societal implications. In this paper, we emphasize the need to integrate diverse spatial entities, such as social actors, natural resources, and infrastructure, into IE frameworks. Drawing on recent developments within the IE community (including insights from the ISIE 2023 conference) we demonstrate how multiple spatialities and politics are already integral to several areas of IE research and practice, such as circularity accounting and industrial symbiosis. We highlight how spatial concepts—such as urbanization patterns, geographic features, territory, place, and actor-networks—reveal context-specific drivers and barriers to circular transformation. We then leverage the concept of scales established across spatial sciences to introduce a typology of scales relevant to IE, and identify which scale types have yet to be operationalized in IE research. Given the potential analytical yield of each scale type, we advocate for a reflective multi-scalar approach to incorporate multiple spatialities into IE research. Ultimately, we call for a spatial turn in re-conceptualizing IE tools to support the transformation of the built environment toward circularity.

KEYWORDS
built environment, circular economy, industrial ecology, material spatiality, scale, social spatiality

1 | INTRODUCTION

In the field of industrial ecology (IE), the concept of spatiality remains inconsistent and underdeveloped despite its recognized importance for enabling a circular economy (CE), particularly in the built environment (BE). Although spatiality is acknowledged in IE studies, it is rarely addressed systematically with the depth required to capture its significance. Both material and social spatiality are crucial for identifying circularity potentials and designing effective strategies for IE systems (Bai, 2007; Bassens et al., 2020). However, IE frameworks currently struggle to address both types of spatiality comprehensively, which limits their ability to develop context-sensitive CE strategies. Existing approaches to material spatiality are fragmented and considerations of social spatiality are largely absent. This gap presents a major challenge in fostering the multilevel governance and spatially informed interventions required for circular transitions (Antikainen et al., 2018).

Material spatiality refers to the physical, objective, and measurable aspects of space, such as physical geography and topological features of IE systems. It includes spatial dimensions that can be quantified, such as distances, land use, and physical boundaries. This concept, traditionally used in IE, focuses on how material and energy flows are organized and managed across different locations. However, even the application of material spatiality in IE frameworks is not yet fully developed, it remains fragmented and lacks systematic consideration (Bahers et al., 2022). Methodologies like input–output analysis, life cycle assessment (LCA), and material flow analysis (MFA) tend to focus on quantifiable aspects of space, but do not sufficiently integrate the full complexity of material spatial dynamics. These dynamics include the physical and geographic relationships between locations or the infrastructural features that affect CE outcomes (Fischer-Kowalski, 1998; Fischer-Kowalski & Hüttler, 1998). This limited consideration of material spatiality prevents a deeper understanding of how physical space and material flows interact in IE systems.

In contrast, *social spatiality*, as conceptualized by Massey (2005) and Löw (2017 [2001]), views space as socially constructed and shaped by human relationships, governance structures, cultural dynamics, and power relations. From this perspective, space is not simply a neutral or fixed entity; rather, it is constantly produced and redefined through interactions among actors, networks, and institutions. Social spatiality is critical for understanding how political, social, and cultural processes influence CE outcomes, particularly in the BE, where urbanization, industrialization, and policy decisions intersect. The absence of social spatiality in IE frameworks hinders IE from addressing how CE interventions and the distribution of resources are shaped by socio-political relations. Without recognizing these social dimensions, IE frameworks risk developing CE strategies that are disconnected from the real-world socio-political contexts in which they operate (Frantzeskaki et al., 2019; Larsen et al., 2022).

The failure to adequately integrate both material and social spatiality into IE frameworks results in a disconnection between the recognition of spatiality as crucial in theory and its selected and unsystematic applications in practice. This is particularly problematic in the context of the BE, where diverse material and social spatial dimensions intersect in ways that are critical to circular transitions. Traditional IE models, grounded in thermodynamic system epistemology, often treat cities as entities detached from socio-political contexts, focusing predominantly on physical material flows (Newell & Cousins, 2015; Wolman, 1965). These models, exemplified by concepts like urban metabolism, tend to oversimplify both the material and social spatial dimensions that arise from interactions between socio-political actors and material infrastructures. This oversimplification could lead to CE interventions that are too context insensitive to address the socio-spatial relations and processes shaping urban and socio-economic systems (Lanau et al., 2021). For instance, while global construction supply chains such as those for metals exert significant environmental impacts across geopolitical boundaries (OECD, 2019), IE frameworks often fail to account for the complex, transboundary nature of these material flows. The reliance of fragmented approaches on material spatiality results in the oversight of key infrastructural and geographical relationships. Moreover, by omitting social spatiality, IE research cannot properly consider how actor-networks, territories, and places influence circular transitions. This double limitation—fragmented material spatial analysis and absent social spatial considerations—constrains the ability of IE frameworks to engage with global–local dynamics that shape the distribution of material and energy flows, as well as their socio-political and environmental implications.

The limited engagement with multiple forms and scales of spatiality in IE frameworks also hampers interdisciplinary collaboration, essential for avoiding negative externalities such as exclusive transition or socio-economic inequality. For example, while buildings in cities are responsible for a significant share of global resource use (Schiller & Roscher, 2023), these same buildings are deeply connected to social issues such as housing and employment (Bugliarello, 2006). Yet, city-level MFA (i.e., traditional urban metabolism studies) or LCA optimization models often overlook such location-specific and spatially specific socio-economic considerations. This gap can lead to unintended or unaddressed trade-offs between circularity goals and reducing social inequalities, broader environmental impacts (Chen, 2021), or other key governance challenges.

At the same time, urban planners and spatial planning researchers could benefit from deeper engagement with IE methodologies to evaluate the resource use and pollution emissions for carbon-neutral, circular developments (Huovila et al., 2022).

Broto et al. (2012) and Kennedy et al. (2011) began discussing the role of planning and design research in understanding space, spatiality, and scale in IE decades ago. Despite the ongoing development (Bahers et al., 2022), spatial concepts are still insufficiently integrated into IE research. By incorporating multiple forms and scales of spatiality in IE frameworks, both the IE and spatial planning communities would have the opportunity to collaborate more effectively. In response to these limitations, we convened a special session at ISIE 2023 conference to discuss the importance of multiple spatiality and scale in transitioning the BE toward circularity. The session stressed that spatiality must be understood not only in material terms but also in social terms. It also highlighted the interconnectedness of material and social, demonstrating how these spatial dimensions mutually reinforce each other in shaping CE strategies. As a result, the growing importance of spatiality within the IE community became evident—an insight that also encouraged us to write this paper, further exploring how spatial considerations—both material and social—could be more comprehensively integrated into IE frameworks.

Rather than developing a new theoretical framework, this paper seeks to provoke discussion and set the stage for more comprehensive conceptual and analytical IE frameworks that fully engage with material and social spatialities. In Section 2, we explore how these forms of spatiality, which have been revealed as relevant in empirical research and policy can inform IE-based circularity strategies in the BE. First, we discuss how material spatiality in relation to urbanization and physical spatial features of locations shapes material flows and CE potentials. Then, we discuss concepts of social spatiality, such as territory, place, and actor-networks, and their impacts on circular transitions in the BE.

Although discussed under two separate sub-sections for analytical clarity, it is important to acknowledge that material and social spatiality are deeply interconnected, as evident in several of the studies cited in this paper. The physical characteristics of space directly interact with the social, political, and cultural ones, which co-shape human activities, influencing and reinforcing the effectiveness of CE. For IE frameworks to effectively address spatiality, they must account for such mutual interdependence. Therefore, we introduce in Section 3 a reflective multi-scalar approach that can support the incorporation of both material and social spatial dimensions across different scales, outlining a pathway toward more integrative and context-sensitive IE-based CE strategies in the BE.

2 | SPATIALITY IN IE RESEARCH AND PRACTICE

2.1 | The multifaceted nature of material spatiality: Urbanization, physical features, and geographic interrelations

Material spatiality in the context of IE is not a straightforward concept but multifaceted and dynamic. In the BE, material flows and CE potentials are influenced by a range of spatial factors, including urbanization patterns, physical features, and geographic relationships. These factors interact in complex ways, and understanding their intricacies is crucial for designing effective, context-sensitive IE frameworks that can enable circular transitions, that is, reducing natural resource exploitation and increase resource efficiency. IE empirical research has shown that material consumption and circular potential vary widely in spatial constellations resulting from specific modes of urbanization. This section explores how material spatiality operates in relation to urbanization, physical spatial features, and location, exposing the layers of its multifaceted nature.

Schiller et al. (2018) demonstrated that building material consumption is generally positively correlated with urbanization rates. However, urbanization is not a uniform process; it manifests differently depending on the socio-economic and geographic context, creating distinct spatial constellations that affect material flows. Schiller and Roscher (2023) illustrated this variability by showing that countries with high urbanization rates consume more building materials than countries in the Global South, where high urbanization dynamics coincide with lower urbanization rates. Furthermore, material spatiality in urbanization differs across economic contexts: in high-prosperity contexts, per capita material consumption decreases as urbanization increases, while in low-prosperity contexts, per capita material consumption rises with increasing urbanization. This variability highlights the importance of tailoring CE strategies to specific regional contexts, ensuring that IE frameworks are responsive to local material spatial dynamics.

Fu et al. (2024) provided further insight by analyzing the material stock of Chinese megacities from 1978 to 2018. They revealed that rapid urbanization leads to a significant accumulation of building materials. However, as urbanization approaches 80%, the relationship between urbanization and per capita material consumption becomes more sensitive. At this point, even a small increase in urbanization results in a disproportionately large increase in per capita material stock. This threshold effect demonstrates the nonlinear dynamics of material spatiality, which must be carefully accounted for in IE models. Such nonlinear dynamics underscore the limitations of IE frameworks that treat material spatiality in a fragmented or overly simplified manner. Understanding these dynamics is critical for designing interventions that are contextually relevant to changing material demands.

Geographic and geometric factors, such as location and physical spatial features, add another layer to material spatiality. Augiseau and Kim (2021) explored the dynamics of material flows within the Paris region and found a negative correlation between population density and per capita material consumption. Despite Paris having a population density four times higher than its adjacent Small Crown region and nine times higher than its distant Big Crown, the per capita inflow of building materials in Paris was one third and one fifth of that in the Small and Big Crowns, respectively. This relationship between urban density and material consumption shows that material spatiality is shaped not just by the degree of urbanization, but by specific spatial configurations within urban regions. Moreover, these spatial configurations are influenced by socio-political decisions related to land use, which play a role in determining the material intensity of urban areas.

Physical spatial features such as geographic proximity to resources and the spatial distribution of infrastructure are critical in shaping the circular potential; especially of non-metallic mineral building material flows, which account for about 90% of materials in BE (Haas et al., 2015). As Roy et al. (2015) and Schiller et al. (2017) highlighted, the geographic location of such construction material sources and their proximity to urban centers play a key role in determining the feasibility of circularity. A region's access to local resources can significantly reduce the need for long-distance transportation of materials. To assess the efficiency of resource allocation and transport related emission reduction in urban regions, the location of specific resources, land, facilities, and their corresponding connectivity indexes (closeness, centrality, clustering, etc.) in a geographically defined functional network—such as the supply chain—are crucial for analysis and evaluation (Cerceau et al., 2018). However, geographic proximity alone does not determine circular potential. Spatial factors like land use, infrastructure, and political boundaries are all interrelated, complicating the picture of material spatiality in any given location.

Zhang et al. (2023) identified other physical spatial features, such as building density, land availability, and urban radius, all of which interact with material flows in ways that are both specific to a region and dynamic over time. Regions with low building density and extensive urban radius, for example, may offer greater opportunities for bulk material reuse, especially in the context of new construction. These features can be mapped and analyzed to develop spatial constellations that inform region-specific circular strategies. Yet, to conduct such mapping is hardly straightforward, as it requires careful consideration of the interplay between topological, geometric, and infrastructural factors. For instance, an area with abundant land may still face resource shortages if its infrastructure is not developed to support material recycling.

In densely populated urban centers like Hong Kong, material reuse and recycling efforts are constrained by spatial limitations. High building density restricts the availability of open space for on-site material processing, such as construction material reuse (Bao et al., 2020). Wang et al. (2010) found that land availability in low-density urban areas seems to be a less decisive success factor for sorting construction waste on-site in China. This exemplifies the intricate ways in which urban density, a key feature of material spatiality, interacts with CE strategies.

To more comprehensively engage with the multifaceted nature of material spatiality, IE researchers have increasingly turned to regional accounting methods and geographic information systems (GIS) to map and analyze material stocks and flows. Schiller et al. (2020) used regional material flow analysis (RMFA) to balance urban material demand with rural material supply, emphasizing the need for spatially sensitive approaches to material management. Similarly, Roy et al. (2015) introduced the spatial allocation of material flow analysis (SAMFA) model, which maps construction material flows at county level and provides insights for spatially informed planning. However, as Liu et al. (2019) pointed out, these models still face challenges in accounting for the full complexity of material spatiality—particularly in integrating spatial heterogeneity, temporal dynamics, and nonlinear interactions between spatial factors. To address these limitations, researchers proposed refining material cadastres and developing digital twins, which allow for a more precise and dynamic representation of material flows across spatial and temporal scales (Lanau et al., 2024, Schiller et al., 2024).

To conclude, material spatiality in the BE is shaped by a range of interacting factors—urbanization patterns, physical spatial features, and geographic–geometric relationships—that influence material flows and CE potential in diverse and often nonlinear ways. Understanding these multifaceted dynamics is essential for designing context-sensitive and comprehensive IE frameworks that can enable circular transitions. However, material spatiality alone does not provide a complete picture. In the next section, we turn to social spatiality—the relational, cultural, and political dimensions of space.

2.2 | The multifaceted nature of social spatiality: Territory, place, and actor-networks

Social spatiality encompasses the relational, political, and cultural dimensions that shape how space is experienced, governed, and organized. Social spatiality influences the allocation of resources, the governance of material flows, and the relationships between actors in ways that material perspectives alone cannot capture.

This section focuses on key aspects of social spatiality—territory, place, and actor-networks—to illustrate its importance and complexity in the CE. These dimensions are not exhaustive but central to understanding how socio-political power, cultural practices, and relational dynamics influence the governance and functioning of industrial systems.

The concept of *territory* in social spatiality refers to the boundaries, authority, and governance structures that define a space and regulate how it is used. In the context of the BE, territory is shaped by local governments, municipalities, and regional authorities, whose decisions determine how land and resources are allocated and managed. From an IE perspective, territory also implies accountability for the environmental and social impacts of development decisions (Cavill & Sohail, 2003; Gordon, 2016).

Municipalities often define the territorial limits for implementing circularity. For example, top-down approaches to CE governance—where local governments or institutions implement policies from a higher level—can significantly shape material flows within a defined territory (Pomponi & Moncaster, 2017). The territorial boundaries of a municipality thus play a crucial role in determining the scope of circular initiatives, from regulating land use to enforcing building codes that promote sustainable construction practices. The European Green Deal Going Local initiative is an example of how regional and municipal authorities are increasingly seen as central actors in advancing sustainability transitions by implementing circular principles (Commission of the European Committee of the Regions, 2020).

However, a territorial approach to circularity is not without its challenges. The effectiveness of territorial policies depends on the alignment of institutional objectives with local realities. Projects such as the Sino-Singapore Eco-City in Tianjin, China, highlight how the failure to integrate local actors and knowledge can hinder circular transitions, despite the presence of strong institutional frameworks. Flynn et al. (2016) pointed out that the lack of shared values and understanding among local professionals and citizens was a significant obstacle to the success of the project.

This underscores the need for IE frameworks to account for the social, political, and governance complexities that arise within specific territories, ensuring that circular strategies are not just imposed but co-created with local stakeholders.

In addition, the territorial governance of circular transitions can encounter limitations if it focuses solely on materials and energy flows, ignoring social and political dimensions. Lazarevic and Valve (2017) argue that some circular initiatives have set vague and uncritical objectives that fail to account for the socio-political realities of the implementation regions. For IE frameworks to be effective, they must consider the power relations, governance structures, and institutional capacities within territories. Understanding territory as a social and political space is crucial for designing more inclusive and effective CE strategies.

The concept of *place* is focusing on the lived experiences, cultural practices, and socio-spatial constellations that define specific locales. It is defined through the interactions and relationships that occur within a space, shaped by social, economic, and cultural conditions (Blotevogel, 2005). From a social spatiality perspective, understanding place is key to grasping how local actors experience, interpret, and influence the CE.

Place-based knowledge and practices, proximity, and local actor involvement (Bahers et al., 2017) are crucial for developing effective circular (urban) systems. Therefore, circularity initiatives must be rooted in the unique social and cultural practices of the locale. For example, the industrial symbiosis in Kalundborg, Denmark, developed through place-based cooperation between local firms, which established strong trust relationships (Ehrenfeld & Gertler, 1997). This cooperation was not coerced by institutional mechanisms but emerged organically from the place-specific dynamics of the Kalundborg community, showing that place-based social constellations can enable more effective circular outcomes.

In addition to the importance of place-based cooperation, the sense of place is a critical factor that influences how local communities engage with CE initiatives. A strong sense of place—defined by how individuals and communities emotionally and cognitively connect with their environment—can lead to higher levels of environmental concern and engagement (Hossu et al., 2024; Vorkinn & Riese, 2001; Wester-Herber, 2004). This emotional connection to place is an underappreciated aspect of CE strategies.

Moreover, place-based innovation often emerges from local contexts, driven by the specific needs and capacities of a community. This includes cultural heritage, which can serve as a valuable asset in CE initiatives, fostering a sense of belonging and connection to local practices while also facilitating innovative approaches to resource use and waste management (Kalakoski & Huuhka, 2018). Similar to the Kalundborg example, by applying the concept of "circuits of value" and the qualitative case study method, Deutz et al. (2024) found that in Hull, England, local place-based development of circular flows generated cross-sector synergies, also revealed social and distributional challenges. These examples illustrate that while place-centered strategies offer opportunities for innovation, they must also be attuned to address local inequalities and socio-economic challenges. In many instances, this means challenging today's mostly profit-driven neoliberal urban development, particularly in Global North (Holub, 2018).

Finally, the concept of *actor-networks* brings attention to the relationships between human and non-human actors—such as infrastructure, technologies, and resources. Actor-network theory (ANT) emphasizes that circularity is not just a social or material process but an assemblage of relations between diverse actors across different spatial scales (Latour, 2005; Laux, 2021). These actor-networks are critical for understanding how CE practices emerge, evolve, and stabilize in different contexts.

Actor-networks extend beyond local boundaries, often connecting global, regional, and local actors in complex supply chains and production networks. For instance, in the Global South, transnational actors such as resource extraction companies and international NGOs play a significant role in shaping urban and industrial development (Robinson, 2021). This global connectivity influences how circular practices are adopted or resisted in different territories, as actor-networks introduce interests and power relations that shape resource use. For example, despite service economies and their global formal networks, recycling in the Global South is often enabled by local informal stakeholder networks.

Leising et al. (2018) demonstrated the importance of actor-network cooperation in the Dutch construction sector, where stakeholders across the supply chain—suppliers, designers, contractors, and waste management companies—collaborated on circular strategies for building, renovation, and demolition projects. Such cooperation highlights how actor-networks facilitate circularity by bringing together various stakeholders with complementary expertise and resources. However, these networks are also shaped by social spatiality, as local power dynamics and relational asymmetries can influence the distribution of benefits and responsibilities within a network.

In a broader sense, ANT helps explain how social and material spatiality interact to shape circular outcomes. The agency of actors—both human and non-human—is influenced by the social context in which they operate, and their interactions reconfigure spatial patterns of development, resource flows, and governance (Babri et al., 2022). As Gailing et al. (2020) argue for the energy transition, circularity transformations in the BE can be expected to lead to contested spatial developments as actor-networks reconfigure relationships between people, resources, and infrastructures.

To conclude, social spatiality is deeply intertwined with the CE's material processes. While concepts like territory, place, and actor-networks are some established conceptual tools to consider social spatiality, they highlight their analytical yields in explaining the formation and consequences of circular transitions. Social spatiality adds layers of complexity that must be accounted for in IE frameworks to ensure that circular transitions are not only technically feasible but also socially inclusive and politically sustainable.

In addition—and as has already become apparent in some parts of the previous text—accounting for multiple spatialities requires consideration and careful integration of multiple spatial *scales*. In the next section, we therefore clarify the various dimensions and analytical yields of *scale* as a concept, and argue for employing a reflective multi-scalar approach to strengthen the analysis and impact of circular strategies on circular transition.

3 | TAKING SPACE SERIOUSLY: A REFLECTIVE MULTI-SCALAR APPROACH

The concept of *scale* is inherent to many research fields focused on human–environment systems such as geography and ecology (Chave, 2013, Levin 1992; Sheppard & McMaster, 2004). The topic of *spatial scale* is particularly discussed in subfields of ecology where spatiality plays a key role (e.g., spatial ecology, landscape ecology, or urban ecology). With IE theoretical foundation drawing from ecological paradigms, and with spatiality being a critical aspect in IE (as argued in the previous section), we find the concept of spatial scale to be a theoretically pertinent notion to IE, one that is becoming progressively viable as IE research on the BE becomes increasingly spatialized (using, e.g., GIS and remote sensing) (Rajaratnam et al., 2023).

At this point, we do not aim to propose a definitive conceptual framework for integrating scale and plural spatiality into IE research on the BE. Rather, we seek to clarify the analytical yields of scale and advocate for a reflective use of multiple scales to incorporate the multiple spatialities ("multi-scalar approach") in IE research and practice. We begin by disentangling the various analytical dimensions and types of spatial scales relevant to IE, discuss their methodological and political implications, and conclude with the new venues we intend to open with multi-scalar IE research.

3.1 | Disentangling the multiple dimensions of scale

Spatial scientists have long agreed that the term *scale* holds two layers of meanings. Scale can refer to the *extent* of a study (i.e., the area encompassed by a study), also to its *grain* (i.e., the size of the individual units of observation) (Wiens, 1989). The concept of *scale as extent* itself holds two analytical dimensions. An extent can be specified using the horizontal and absolute measure of *size*, as in "one hundred square kilometers." An extent can also be specified using the *level* dimension—as in, "at national level"—a constructed and vertical measure that refers to "a nested hierarchy of differentially sized territorial units" (Brenner, 2016; Delaney & Leitner, 1997; Howitt, 1998; Taylor, 2004).

In addition to the analytical dimensions of scales summarized above, the existence of multiple definitions and types of scales created ambiguities and confusion within and across geoscience disciplines, especially the more abstract dimensions of scales. (Dabiri & Blaschke, 2019). Thus, before discussing the benefits of a multi-scalar approach to IE, and given the multidisciplinary profile of IE research, we seek to minimize ambiguities by presenting a typology of spatial scales relevant to the spatialization of IE. We adapted the typology from the article "Scale matters" by Dabiri and Blaschke (2019), who reviewed the existing typology of Wu and Zhao-Liang (2009) and adapted it to a cross-disciplinary context.

The most common use of the term spatial scale in science refers to the "cartographic scale," or map scale, which expresses the ratio between distances on a map and real-world distances (Lloyd, 2014). However, this concept offers little analytical depth and we have thereby incorporated five other scale types here. First is the "geographic scale," which refers to the spatial extent of the research area. This scale is frequently used in IE to describe the studied system and is termed as geographical boundary or scope. For example, in their modeling of construction material stocks from satellite data, the geographical boundary of Haberl et al. (2021) is Austria and Germany (here, the extent is defined using the level dimension, i.e., national).

The "measurement scale" and "modeling scale" both refer to spatial grain and are often interchangeably termed as spatial resolution despite being distinct from one another. The measurement scale refers to the spatial granularity of the data acquired while the modeling scale refers to the spatial granularity of the model derived from the data. As such, the modeling scale is constrained by the measurement scale, and the former should also be aligned with the operational scale (discussed later) to reveal the system under study. In their study, Haberl et al. (2021) used satellite data with a measurement scale of 10 m, which allowed them to model material stocks in the BE at several modeling scales, the finest of which was 10 m—as constrained by the measurement scale.

The "operational scale" refers to the scale at which the specific system/process/feature under analysis operates. When conducting a study, and where the analytical approach allows it, the traditional bounded territorial perspective should be replaced with a more dynamic, open-ended, and cross-border perspective centered on the actor-network associated with material flows. The grain dimension should also be chosen carefully so that the variability of the system/process/feature under study may be captured—this also requires the modeling scale to be finer than the operational grain.

The "policy scale" denotes the scale at which policies and decisions are formulated, implemented, and evaluated. Both operational and policy scales are relevant to the delineation of system boundaries. The notions of operational and policy scales do not pertain to the *size* dimension of scales but to the *level* dimension, and thus to the aforementioned notion of verticality and of a nested hierarchy of differentially sized spatial units. Selecting the appropriate operational scale level ensures the system boundaries are aligned to the system/process/feature under analysis and its relevant stakeholders. In addition, where the aim is to inform decision-making, the scale at which to analyze a system/process/feature should be chosen appropriately. Such a choice should leverage strategies, policies, and implementation measures at the right administrative levels or level of action. Finally, the appropriate policy scale must be selected when analyzing a system/process/feature to inform decision-making and the policy scale should ideally match the operational scale so that reliable conclusions may be drawn from the analysis.

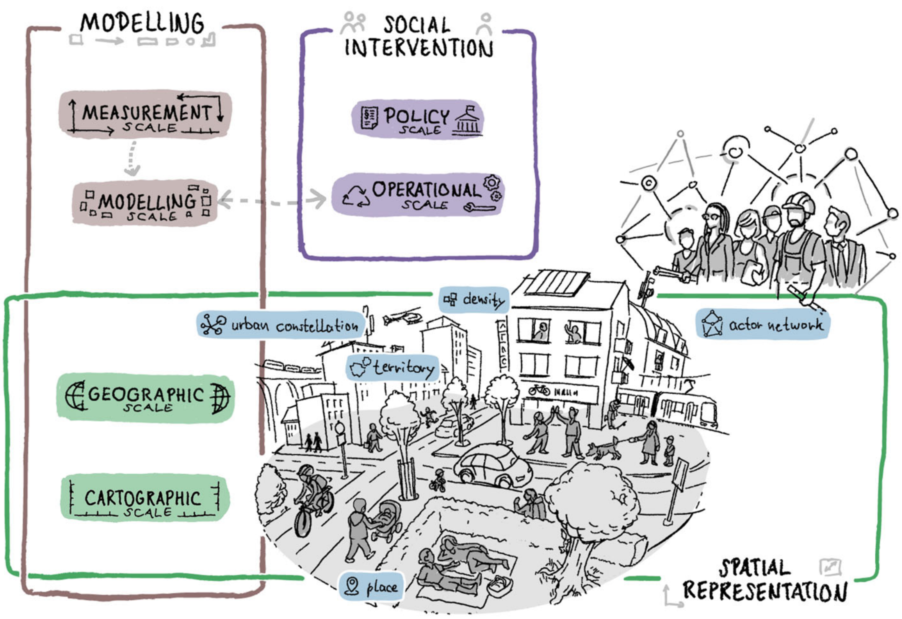

FIGURE 1 Multiple spatialities and scale as an integrative and cross-cutting concept.

The typology of scale outlined above encompasses various analytical dimensions—including extent, grain, and level—and at the same time both concrete concepts, such as map scale, and more abstract ones, such as operational scale. As discussed above, the study and assessment of circularity strategies in the BE is complex and requires an approach that integrates material and social spatialities. In this regard, we echo landscape ecologist J. A. Wiens (1989) and support that industrial "ecologists therefore need to adopt a multi-scale perspective."

3.2 | The politics of scale

A multi-scalar approach, as outlined above, conveniently accounts for the politics that emerges from considering the material and social spatialities relevant to IE research on circularity in the BE. The horizontal, *sized* model of scale defines the extensiveness; it bounds the material entities upon which control is exerted and contested. The vertical, *hierarchical* model, has important implications for social and policy actions in CE in terms of how—and at which level—best to link social relationships, for highlighting and fostering alternative social innovations (Leitner, 2004), and to adequately integrate a consideration of sense of place and belonging as introduced above. Both *sized* and *hierarchical* models of scale come with an integral political dimension. By making this explicit, politics can be introduced back into IE research, thus ensuring a better understanding of how to effectively propose and implement circular strategies.

The relevance of stakeholders in scale selection echoes discussions in the special session during which participants pointed out that while the modeling scale may inform stakeholders, stakeholders should also inform the modeling scale—for example, by introducing place-based perspectives and knowledge. This is particularly important since the chosen modeling scale should match not only the measurement scale, but also the operational scale, otherwise the spatial variability of the process/feature under investigation may be lost. As expressed by Wiens (1989) and Levin (1992), there is no single "correct" scale to describe ecosystems, as the interaction among patterns and processes happen on—and thus should be analyzed at—different scales. This resonates with the systems perspective of IE and with the concept of hierarchical scales discussed in our special session and in some of the IE literature (Moffat & Kohler, 2008; Stephan et al., 2022). We abstain from taking hierarchical scale and its derivatives (e.g., local vs. global) as self-evident or unquestionable spatial fixity. Rather, we argue that questions of significance, appropriateness, and understandability of different scales for different processes, purposes, and CE actors ought to be investigated case by case. In this regard, the current integration of high-resolution spatial data to IE offers opportunities to aggregate and disaggregate results across different modeling scales.

Figure 1 illustrates the discussions of this and the previous section graphically and reflects the embedding of the BE and its spatial dimensions in a multi-scale approach. This multi-scale approach helps considering social and political intricacies associated with the transformation of the BE. Nevertheless, it should be noted that although the scalar approach brings to the fore some of the previously neglected questions about politics, it is also important to recognize that the politics of circularity deserves its own theoretical endeavor and its own chapter in the IE spatial turn and can only be touched upon in this paper.

4 | CONCLUSION

Since the "spatial turn," the notion of space has been invoked by scholars beyond geography to understand how social processes are entangled with material processes in different locations (Lefebvre, 1991 [1974]; Löw, 2017 [2001]; Massey, 2005). Generating an understanding of such entanglements is also at the core of IE research interests. Through our discussions on the multiple spatialities embedded in IE research topics, we have shown the rich opportunities for dialogues between scholars from IE and social–geographical disciplinary backgrounds. Such efforts and dialogues are increasingly reflected in various research efforts of the IE community. These include conference sessions such as *"Does space matter?—Transition of built environment towards circularity in a spatial context"* at the ISIE 2023 conference, a special issue on *"Spatialized material stock analysis to facilitate circularity of the built environment"* (Lanau, Tingley, et al., Eds. 2024), and international research group development such as the ISIE Circular Economy Section who reflected on spatial and scale issues under the topic "location" in their white paper "*Ten insights from industrial ecology for the circular economy*" (Ewijk et al., 2023). However, the majority of IE research is still based on a narrow Cartesian understanding of space and relies on very constrained spatial types in practice. The same applies to the associated understanding of scale, which primarily refers to administrative hierarchy. The reflective multi-scalar approach outlined is an important contribution to making IE more impactful by considering social and political intricacies that strongly influence the outcomes of any transformational effort. However, transformation-oriented IE research, which is what the change from linearly organized BE to a circular system is all about, cannot stop here. In particular, the inclusion of place and actor-network analysis in IE research frameworks is essential for understanding and stimulating cross-functional and place-based transformations. We acknowledge that challenges of integrating multiple spatialities remain. For example, how can GIS-based tools that build on a Cartesian space epistemology be integrated with a perspective on actor-networks and place? In this context, the proposed scale categories and their interweaving with multi-spatiality dimensions can provide significant support in the design of CE strategies and in their modeling and evaluation tailored to the needs of stakeholders.

As spatial configurations can be understood as being subject to a process that is inherently dynamic and unfolds in time, the temporal dimension is an inherent element of the spatial concepts we present. However, since these are based on very different epistemological foundations, the conceptualization of the temporal dimension is assumed to be plural. We believe that the different temporal dimensions and their synchronization or dyssynchronization are crucial for understanding the success of circular transitions in places. However, discussing this aspect in detail is beyond the scope of this paper, but is worth exploring in more detail in future discussions.

Regardless of this, for IE to effectively support the transformation of the BE toward circularity, it seems urgently necessary to open up perspectives, concepts, and methods and to incorporate space and scale in their multidimensionality. As shown by the interest of the IE community in the special session, this paper refers to, this is a very timely proposition and meets a great need of the scientific community. This is about nothing less than a spatial turn for industrial ecology.

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The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

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

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