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COMMENT

Towards an integrated understanding of circularity, urban design, planetary stability and well-being

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Abstract
Circularity strategies are increasingly recognized as essential for reducing greenhouse gas (GHG) emissions and improving material efficiency in urban environments. However, existing approaches often analyze sectors in isolation, limiting their ability to capture systemic interactions and spatial dependencies. In this study, we introduce the Integrated Urban Circularity (INTURC) framework that integrates construction, building energy use, transport infrastructure, waste management, and overarching urban planning strategies to guide consistent modelling efforts. INTURC enables the explicit identification of both cross-sectoral circularity policies, which generate synergistic effects across multiple urban systems, as well as domain-specific interventions with more localized impacts. In contrast to established circularity modelling, we suggest capturing the spatial relationships in context of the social setting and policy designs that shape circularity outcomes, such as destination accessibility, information feedback and infrastructure reuse. By embedding circularity strategies within institutional and urban design contexts, INTURC facilitates systemic assessments that support effective policy prioritization.

Keywords Industrial ecology · Urban metabolism · Circular economy · Spatial relations · Institutional design · Climate mitigation

1 Introduction

Circularity is advocated as a key strategy for enhancing material efficiency across supply chains, offering pathways to mitigate environmental challenges in an increasingly resource-constrained world (Blomsma & Brennan, 2017; Korhonen et al., 2018). In particular, the climate mitigation potential of circularity has received academic attention with findings indicating (sometimes limited) potential to reduce greenhouse gas (GHG) emissions (Cantzler et al., 2020; Murray et al., 2017; Pauliuk et al., 2021; Wiedenhofer et al., 2024a, 2024b). Cities are central to reducing, reusing and recycling material in line with circularity, as large proportions of global materials end up in cities as consumables,

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municipal waste, or accumulate in urban infrastructure (Abunyewah et al., 2023; Calisto Friant et al., 2023; Lakatos et al., 2021; Vanhuyse et al., 2021a, 2021b; Williams, 2021). For instance, 38% of all waste in the European Union is related to construction and demolition of infrastructure and buildings (Eurostat, 2024b).

At the same time, cities are inherently interconnected places in which multiple sectors and impacts intersect in space and time, requiring an integrated perspective for understanding circularity in urban environments. The location of buildings can reduce travel and infrastructure demand (Creutzig et al., 2016), the repurposing of buildings involves adapting from commercial to residential use (Gursel et al., 2023), the lifetime of concrete from buildings is extended by application in road bases (Watari et al., 2022), desealing of urban surfaces reduces asphalt use while enhancing water infiltration and urban cooling (Aimar, 2023), GHG-intensive combustion of fossil fuels goes along with exposure to air pollution (Lelieveld et al., 2023), and people with diverse cultural positions live alongside each other requiring careful institutional design for equity and inclusivity (Chu & Cannon, 2021). As we will argue throughout this paper, circularity interventions in urban environments have a systemic effect affecting subsystems, use patterns, urban planning, and transformation trajectories; and the effectiveness of those interventions is moderated by urban and institutional design which link various subsystems. Hence, it does not suffice to model circularity potentials in single sectors such as buildings or on single outcomes such as GHG emission. Instead, the evaluation of circularity strategies in urban environments requires consistent application of integrated operational models that span various sectors, impacts and spatial and institutional configurations.

As a discipline, industrial ecology has contributed significantly to the conceptualization and measurement of urban circularity (Bortolotti et al., 2023; Kennedy, 2016; Wuyts et al., 2022). Impactful studies have explored urban metabolism through material and energy flow analysis (MEFA) quantifying onsite resource use, stocks, waste, and emissions, as well as up- and downstream effects (Bai, 2016; Christis et al., 2019; Haberl et al., 2023; John et al., 2019; Kennedy et al., 2011, 2015; Papageorgiou et al., 2024; Pauliuk et al., 2014). These approaches have emphasized understanding the stocks and flows of materials and energy in urban systems and their global hinterlands, revealing critical hotspots and opportunities for intervention.

However, while valuable, these methods typically focus on accounting and do not fully capture the dynamic interplay between sectors mediated by institutional design or the explicitly spatial dimensions of urban design (Bahers et al., 2022). For instance, circularity scenarios in the building sector tend to not consider potential impacts on transport patterns and infrastructure (Mastrucci et al., 2023; Napiontek et al., 2025; Pristerá et al., 2025; Berrill & Hertwich, 2021), or only evaluate impacts on energy use disregarding implications for material use (Dujardin et al., 2014; Gaur et al., 2024). Systematic reviews of climate mitigation assessments repeatedly find that studies on even the same circularity strategy are incomparable due to inconsistent system boundaries, diverging reported indicators, and disciplinary assumptions (Cantzler et al., 2020; Wiedenhofer et al., 2024a, 2024b; Bortolotti et al., 2023). In practice, local governments almost exclusively monitor effects of circularity strategies on climate change mitigation, while targeting various environmental and social concerns (Kopp et al., 2024). This fragmented approach to circularity assessment, assessing changes in single sectors or impacts, limits understanding the potential that lies in cross-sector reuse and sharing of material and of potential side-effects that may result as a consequence of implementing circularity in one sector with a specific policy design.

Few studies have started integrating aspects of urban and institutional design in circularity assessments. Case studies have explored the integration of agent-based models with techno-economic models of single sectors or companies portraying selected influences of institutional design (Baumann & Lindkvist, 2022; Walzberg et al., 2023). Spatially explicit dynamic stock models are rare, and when they do exist, they often focus on individual sectors (Berrill & Hertwich, 2021), limiting their ability to identify total circularity potential. Further, such cartesian spatial dynamic material stock and flow models are rarely situated in institutional contexts that consider how and by whom changes are enacted and who is affected (Bahers et al., 2022). Thus, scholars have recently called for a spatial turn in industrial ecology research to consider influences of diverse spatiality concepts including geometric measures, territorial jurisdiction, and place (Schiller et al., 2025). What is missing is an integrated framework that unifies these emergent approaches and provides direction for future model developments.

To unify these fragmented efforts into a consistent modelling agenda, we introduce the Integrated Urban Circularity (INTURC) framework. INTURC is meant to serve as a pre-modelling screening tool to assist in identifying the relevant dynamics that need to be captured for the consistent evaluation of specific urban circularity strategies. Thereby, the framework can motivate for instance the collection of geolocated, behavior response and socially stratified data alongside aggregate material flows. Based on our multidisciplinary perspectives, this emergent operational framework connects sectoral strategies in construction, transportation, building energy use, and waste within a unified urban context. By incorporating spatial and systemic considerations, INTURC facilitates robust

"apples-to-apples" comparisons and integrated modelling that provides insights into the systemic effects of circularity strategies to enable effective prioritization of interventions.

2 System level components of urban circularity

The first step for designing an integrated urban circularity framework is to define the essential components and dimensions such a modelling framework needs to cover.

2.1 Sectoral practices

At its core, INTURC needs to account for material and energy use and the associated material stocks across sectors and within practices that are relevant for planetary stability and well-being (Desing et al., 2020; Vanhuyse et al., 2021a, 2021b). Mass-balanced and thermodynamically correct accounting is central to providing a solid quantitative grounding of effect sizes, which is at the core of the discipline of industrial ecology (Ayres & Ayres, 2002; Cullen, 2017; Streeck et al., 2024). In urban transport, GHG emissions are driven by infrastructure development and vehicle production and operation, requiring accounting for the full lifecycle from construction materials through to energy consumption (Chester et al., 2010). For both transport infrastructure and buildings, three key parameters are important to capture: the intensity of use, the technology mix and the volume of use. For instance, a combined analysis on the decarbonization of the US housing sector highlights the need for retrofits (intensity), heat pumps (technology) and reductions in per capita dwelling size (volume) (Berrill et al., 2022). While industrial ecology research has focused on understanding the physical quantities and qualities of material and energy used, behavioral and practice research is highlighting the motivation, meanings and competences that underly these physical flows (Haberl et al., 2021).

2.2 Urban environment

Crucially, changes in sectoral practices towards circularity all take place in explicitly spatial settings and are closely connected in their spatial relationship – an aspect typically not covered in industrial ecology studies (Inostroza & Zepp, 2021; John et al., 2019; Bahers et al. 2022; Schiller et al., 2025). Hence, a central and innovative element of the INTURC framework is the consideration of urban design, which matters in relating different circularity strategies and for including higher order effects. For example, a key urban climate mitigation strategy is compact urban forms enabled by strategic re-densification plans, superblocks or compact zoning regulations on the urban fringe (Brenner et al., 2024). These minimize the need for extensive road networks and associated asphalt requirements while also reducing reliance on car-based transport and lowering heating demand (Creutzig et al., 2016). Similarly, depending on the proximity of supply and demand, repurposing components of obsolete infrastructure can generate freight transport that may surpass the emission savings from material reuse (Cooper & Gutowski, 2017; Wang et al., 2023). Notably, urban design goes beyond the location of infrastructure and materials and encompasses the quality, meaning, form and shape of urban spaces. For instance, the same material use for a building can incentivize different occupancies, interactions and sharing behavior depending on the layout and acoustic quality (Denstadli & Sønstebø, 2025; Malmqvist & Brismark, 2023).

By combining these elements, INTURC aims to guide systemic assessments that integrate material and energy flow analysis with spatially explicit accounting of stocks, services and impacts for evidence-based prioritization of circularity strategies.

2.3 Social setting

Outcomes of urban circularity are also significantly influenced by institutional design and social settings, as these establish the frameworks for policies, behaviors, and innovations to emerge and thrive. Regulations, incentives, and norms provide the enabling environment for urban functioning and circular practices and define distributional effects, while demographic factors, values, and political systems shape their adoption and scaling. For instance, policy instruments such as tax incentives and mandatory recycling quotas drive circular practices in urban housing projects by creating predictable pathways for stakeholders to invest in circularity innovations (Bucci Ancapi et al., 2022). At the same time, the specific design and selection of incentive mechanisms require special attention as it influences the distribution of winners and losers in circularity transitions (Lindsey et al., 2023).

Social values and demographic trends also play a critical role in moderating effect sizes of circularity strategies. Demographic shifts may contribute to the cultural acceptance and normalization of circularity principles in urban contexts as younger populations push for innovations such as shared mobility and zero-waste systems (Fratini et al., 2019). On the contrary, the trend toward single person households and urbanization complicates the transition to higher material efficiency by driving up demand for dwellings in some locations while leaving part of the existing building stock stranded (Ellsworth-Krebs, 2020). These demographic tendencies are also relevant with regards to urbanization. While urban settlements tend to have lower resource use due to their higher densities and greater feasibility of public

transport, aging populations and smaller household sizes in urban areas reduce efficiency of resource use (Natale et al., 2023), motivating greater attention to demographic transitions and spatially explicit demand. Political systems frame the prioritization and implementation of circularity policies (Cramer, 2022). Transparent governance and localized stakeholder-inclusive decision-making have been shown to accelerate circularity transformations in cities by effectively tailoring strategies to regional needs and socio-spatial dynamics (Soto et al., 2024).

2.4 Outcomes

Finally, understanding the side-effects of circularity strategies also requires maintaining a cross-impact view on various outcomes in line with established approaches in urban planning that facilitate the balancing of interests (Schiller et al., 2025). Urban circularity aims at achieving outcomes encompassing both well-being and planetary stability that align with the Sustainable Development Goals (SDGs) (Kopp et al., 2024). Well-being outcomes, as measured in (Creutzig et al., 2022a, 2022b; Creutzig et al., 2022a, 2022b), emphasize dimensions relevant for individuals, including health and equity, while planetary-stability outcomes address critical environmental metrics such as GHG emissions, biodiversity preservation, and resource depletion. Together, these outcomes correspond to the OECD's WISE (Well-being, Inclusivity, Sustainability, and Equity) framework (Liu et al., 2024).

3 The integrated urban circularity framework

The integrated urban circularity framework, INTURC, connects these four essential system level components and dimensions into an emergent operational framework providing a blueprint for considering relevant dynamics that influence circularity outcomes in cities (Fig. 1). It relates societal structures and institutional designs to the physical

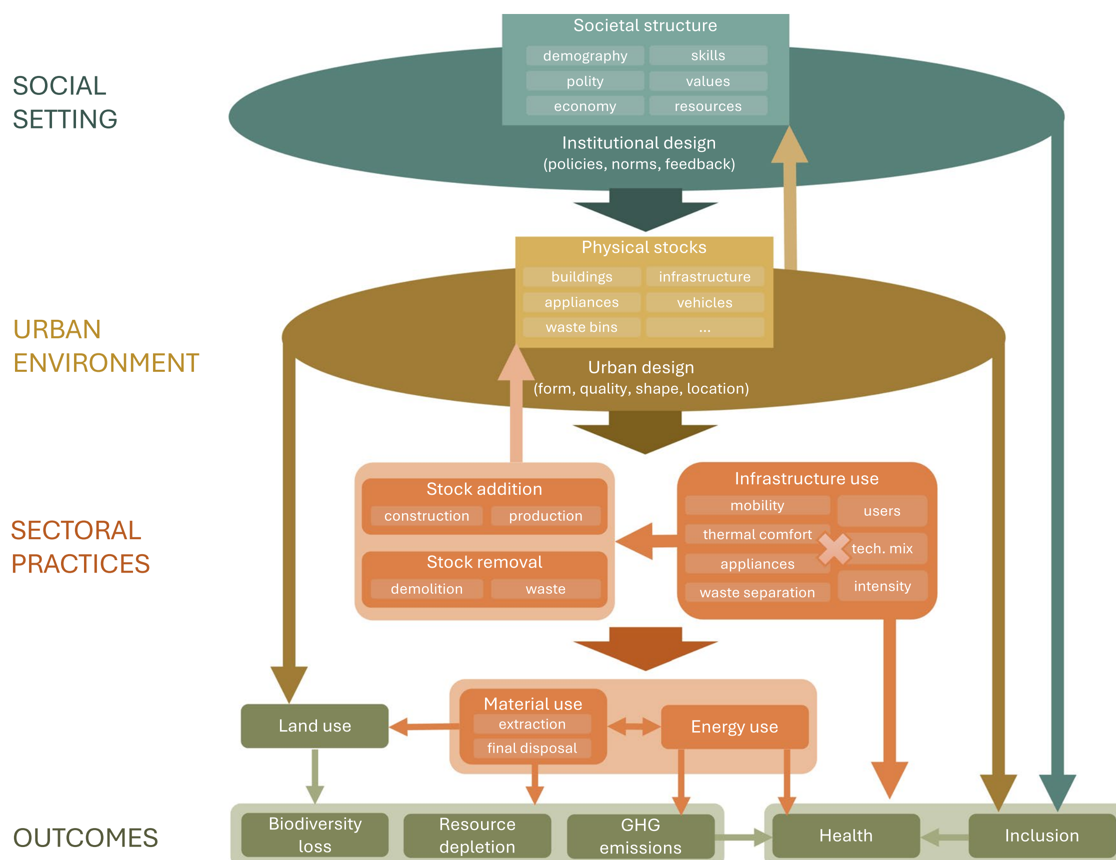


Fig. 1 The integrated urban circularity framework INTURC captures the interconnected relationships between social settings, urban environments, sectoral practices, and outcomes. INTURC shows how institutional and urban design moderate resource flows, and systemic impacts on planetary stability and well-being outcomes. Arrows indicate influence, the cross indicates that each property of infrastructure use (number of users, technology mix, use intensity) can apply to each domain of infrastructure use (mobility, thermal comfort, appliances, waste separation)

composition and design of urban environments which in turn drive sectoral practices that result in measurable environmental and well-being outcomes (see Supplementary Information SI2).

At the top level, the social setting encompasses demography, economy, skills, and values, alongside institutional designs such as policies, norms, and feedback mechanisms. These elements drive urban systems, influencing how resources are allocated, how policies are framed, and how behavioral norms are established. This in turn shapes the urban environment, which includes physical stocks such as buildings, infrastructure, vehicles, appliances, and waste-collection infrastructure such as household bins. Urban design, defined by quality, form, shape, and location, acts as a critical mediator in this relationship, influencing how physical elements are configured and utilized. The existing urban stocks and their design in turn influence and are influenced by sectoral practices including stock addition (including construction of buildings and infrastructure and production of items such as vehicles or appliances), stock removal (demolition and waste handling) and infrastructure use. Infrastructure use, encompassing mobility, energy for thermal comfort and appliances, and waste separation, represents the functional aspect of these systems. These sectoral practices consume resources, generate waste, and produce emissions, directly linking urban and institutional design to environmental and well-being outcomes. The outcomes encompass intermediate metrics such as land use, material use, and energy use, which culminate in broader planetary impacts such as biodiversity loss, resource depletion, GHG emissions, and well-being dimensions such as health and inclusivity—indicators for evaluating the performance of urban circularity strategies.

INTURC integrates social and institutional dynamics with the physical and functional aspects of urban systems. The framework relates stock and flow accounting with spatial design and (urban) institutional settings, offering a holistic perspective missing in traditional models. INTURC thus enables the identification and evaluation of leverage points, including how values and policies can shape urban design to optimize outcomes.

4 Application: revealing relevant dynamics of diverse circularity strategies

To understand how the INTURC framework helps identifying the dynamics relevant to evaluating specific urban circularity strategies, we exemplify an analysis using a set of diverse leverage points. In the following, we first introduce the selected leverage points (Sect. 4.1), describe the cross-sector effects relevant to these levers (Sect. 4.2), evaluate the extent to which current GHG and material assessments capture these cross-sector effects (Sect. 4.3), describe cross-impact synergies and trade-offs of these levers (Sect. 4.4) and elaborate on barriers and enablers identified using the framework (Sect. 4.5). We conclude with a suggestion for improved modelling of the six leverage points guided by the INTURC framework (Sect. 4.6).

4.1 Six diverse circularity leverage points

We select six different leverage points promised to mitigate GHG emissions that span different sectors as well as design, use and stock accumulation processes: (1) High-accessibility residential planning primarily targets the reduction of transport infrastructure and use-related GHG emissions through changes in urban design with broader effects on energy use for thermal comfort and on land use. (2) Floor area intensification primarily targets reduction of construction-related emissions with broader effects on reduced building energy use, land use and health. (3) Repurposing obsolete infrastructure primarily targets infrastructure-related emissions with broader effects on transport energy use and reduced resource depletion. (4) Material substitution primarily targets construction-related emissions with potential further effects mediated by constraints in building design. (5) Electricity load shifting primarily targets electricity generation related emissions through changes in the timing of electricity demand with potential broader effects mediated by the specific location in which electricity is used. (6) Normative feedback for waste separation primarily targets disposal-related emissions through changes in institutional design.

We choose the leverage points for their capacity to address diverse aspects of resource efficiency and climate change mitigation across spatial and systemic domains. The leverage points comprise strategies addressing emissions from transport, construction and household consumption, as well as requiring changes in urban planning, production decisions and household behavior in line with recent conceptualizations of leverage points (Baumann & Lindkvist, 2022; Haas et al., 2026). Our selection reflects the effectiveness in scaling solutions with spatial scope, mitigation potential, systemic effects, and feasibility within complex regulatory frameworks (Fig. 2, see Supplementary Information SI3). Our findings here are conceptual and motivate further quantitative model operationalization and refined evaluation.

4.2 Cross-sector effects: buildings, energy, transport and waste

The analysis reveals several cross-sector effects of the six leverage points (Fig. 3). In the circularity context, both floor area intensification and electricity load shifting are motivated by limiting infrastructure expansion (such as

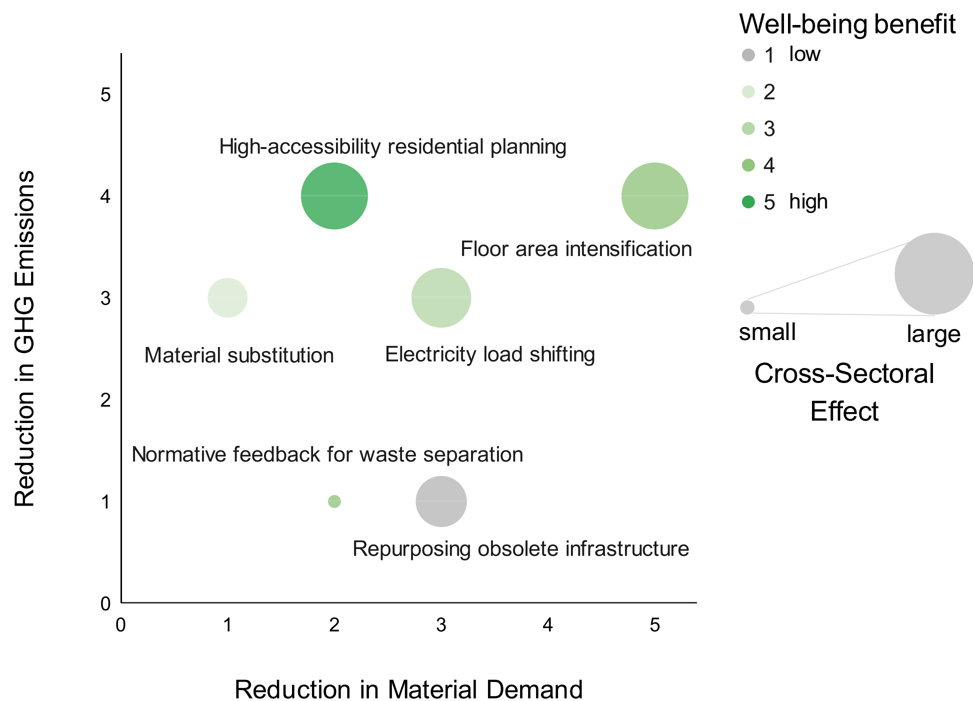


Fig. 2 Effects of each leverage point on greenhouse gas (GHG) emissions, material demand, and well-being outcomes, with additional indication of cross-sectoral scope. Assessment based on expert judgement by authors and justified by analysis and tables in main text (see Supplementary Information SI4)

buildings, power plants and grid infrastructure) and related material requirements. Yet, both levers are also associated with changes in building energy use, which itself may have effects on emissions and other outcomes. For instance, lower floor area per capita translates to lower heating demand per capita (Lorek & Spangenberg, 2019; Ness, 2020), whereas electricity load shifting may facilitate a higher share of renewable energies (Desing & Widmer, 2022).

Circularity strategies may also induce changes in transport energy demand mediated by urban design. The extension of material lifetime by repurposing obsolete infrastructure only yields a net environmental benefit if the obsolete infrastructure is available close to the location where the material is needed because otherwise the additional freight transport outweighs the material savings (Wiedmann, 2024). Similarly, separate waste collection requires a certain level of population density to be emission-effective (Romano et al., 2022). In contrast, increasing population densities through high-access residential planning or floor area intensification in accessible locations results not only in lower infrastructural requirements but also less emission-intensive travel (Nachtigall et al., 2024). Floor area intensification by reuse of remote building stock can, on the other hand, increase emission-intensive travel ceteris paribus. Urban design in these cases shapes material and energy efficiency through spatial–temporal co-location. This underlines the importance of contextualizing the circularity strategies in space.

The cross-sector effects revealed with these examples highlight the need to account for transport and operational building energy use next to waste and material use related to circularity strategies.

4.3 Gaps in carbon and material efficiency estimates

Knowledge about the comprehensive effects of circularity strategies is sought to rank and prioritize measures. Yet, despite significant resources invested, assessments still often fail to comprehensively account for the cross-sector effects that INTURC reveals (Table 1). For instance, while high-accessibility planning and electricity load shifting hold potential for limiting infrastructure expansion and shifting energy demand, quantitative evaluations currently focus on the technology shift potential – from emission-intensive to low-carbon technologies (car to public transport and cycling, fossil fuels to renewables) (Ibraeva et al., 2020; Mata et al., 2020). Applying the qualitative insights yielded through INTURC, we can expect these emission reduction estimates to be rather lower bounds.

In contrast, the adaptive reuse of latent material and functional resources such as existing floor area or obsolete infrastructure is often evaluated in terms of material savings (Jiang et al., 2023; Napiontek et al., 2025; Pauliuk et al., 2021), ignoring further effects of infrastructure use down the line. While quantified marginal effects on material requirements are substantial (Table 1), the use-phase effects depend on the specific design of the intervention.

For instance, the reuse of material from old gas pipelines for district heating pipelines could accelerate the deployment of district heating and the transition from fossil fuels to renewables—the emission-savings of which are still to be quantified (Wiedmann, 2024). Similar effects might also hold for cost-saving measures such as electricity load shifting where investments not needed for energy storage and grid infrastructure could be redirected to accelerate solar and wind capacity build up (Desing & Widmer, 2022).

Two interventions for which an active debate and competing quantifications around intertwined effects have emerged are material substitution with wood and waste separation. In wood construction, evaluations that account for land use change, find a lower emission saving potential compared to those that only consider fuel combustion and carbon capture in wood (Duan et al., 2025). For waste separation, various accounting procedures have been debated in the context of life cycle assessment from those including impacts on avoided landfilling to those mainly accounting for the environmental benefit of replacing virgin materials (Schrijvers et al., 2016).

Across strategies, a challenge remains to understand the elasticity of practices which is crucial for appropriate ranking and prioritization. While the calculation of technical potentials is rather straightforward, the social setting of INTURC emphasizes specific conditions that are required to leverage technical potentials. For instance, co-housing and vertical extension of buildings in accessible neighborhoods have likely the most encompassing technical potential for emission reductions (simultaneously addressing material, energy use in building and transport and land use) but face barriers related to hassle and upfront cost (de Vries et al., 2020; Gillott et al., 2022). For the case of normative feedback, this has been approached using field experiments (Bonan et al., 2025). For floor area intensification, survey-based approaches with willingness to reduce floor area are taking hold (Heylen & Vanderstraeten, 2019; Pfnür et al., 2023).

Overall, the strategies vary in their effectiveness at reducing GHG emissions related to material use, with their impacts largely depending on the sectors they target, their mechanisms for change, and local context (Table 1). Certain circularity leverage points, such as floor area intensification and load shifting, align well with the framework but remain underexplored in integrated spatial urban contexts. The spatial implications of these levers, including the redistribution of resources and population, which may involve place-based policies, highlight the need for further research to evaluate their systemic impacts in urban settings (Napiontek et al., 2025). Other leverage points are highly specific, such as repurposing obsolete gas pipelines into district heating systems (Wiedmann, 2024). While their overall relevance may be limited, understanding the trade-offs and marginal benefits of such strategies helps refine priorities and assess their greater systemic impact. An integrated assessment provides valuable insights for broader applications of circularity principles.

4.4 Cross-impact effects: synergies and trade-offs

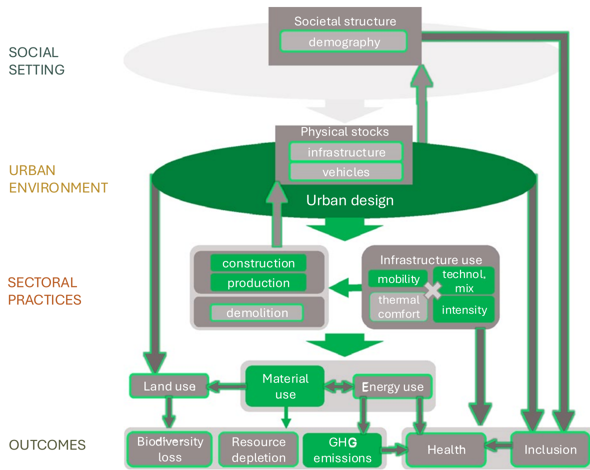
Analysis with the INTURC framework reveals potential synergies and trade-offs of the leverage points on planetary stability and well-being which ought to be taken into consideration when aiming at a comprehensive evaluation of circularity strategies (Table 2). Urban and institutional design play a crucial role in shaping the synergies and trade-offs of circularity interventions, with outcomes highly dependent on local context and implementation. By aligning infrastructure, regulations, incentives and information, urban systems can achieve both environmental goals and enhanced well-being.

Potential trade-offs, for instance, become apparent with material substitution with bio-based material which –despite enabling lightweighting and lower fossil fuel combustion– may induce land use changes that affect biodiversity and carbon cycles (Churkina et al., 2020). Such trade-offs mediated by spatiality also are relevant in the case of floor area intensification in high-access locations which may affect mental health via a reduction in private space and increased exposure to noise and air pollution (Pont et al., 2021). Yet, depending on the demographic addressed, floor area intensification policies could also improve mental health by reducing loneliness (Carrere et al., 2020).

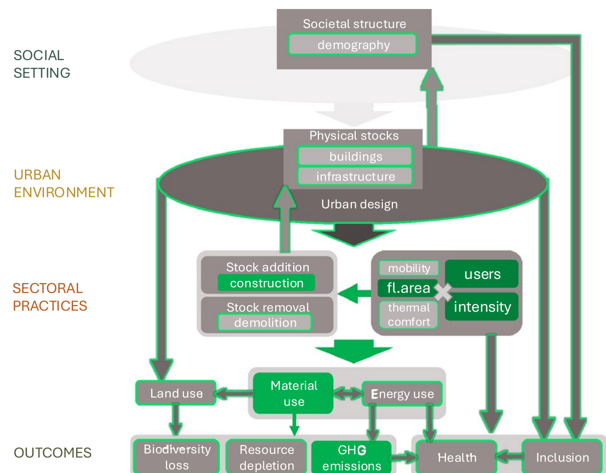
Next to health benefits, synergies mediated by urban design identified using INTURC relate to land use and additional GHG emission savings. For instance, the lower requirement for infrastructure expansion in both electricity load shifting and floor area intensification, translates to less anthropogenic land use. Similarly, less soil sealing for roads is required in the high-access residential planning case in which existing infrastructure is more efficiently used. Where improved waste separation deviates waste from landfills to recycling, less land is required for landfills which not only reduces methane emissions but also toxic landfill leakage. Additional GHG emission savings are mediated by the cross-sector effects previously described. For instance, the lower energy demand in case of floor area intensification can translate into emission savings from both material and energy demand.

Next to urban design, institutional design is key to realizing well-being and equity outcomes of circularity strategies. For instance, incentivizing waste separation through higher prices for unsorted waste can lead to trade-offs on affordability and equity, however information feedback on waste disposal can reduce the need for additional price signals (Bonan et al., 2025; Ek & Söderberg,

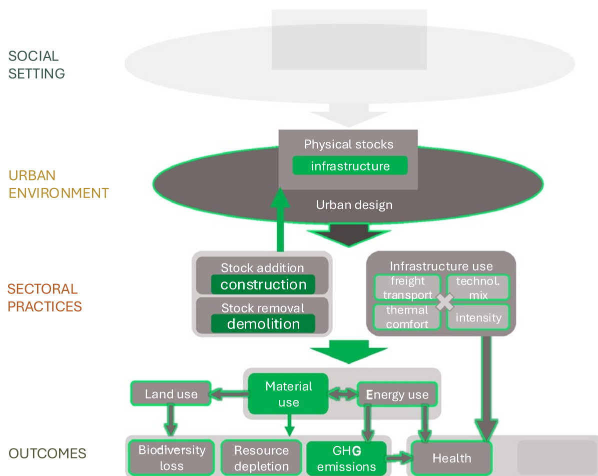
High-accessibility residential planning



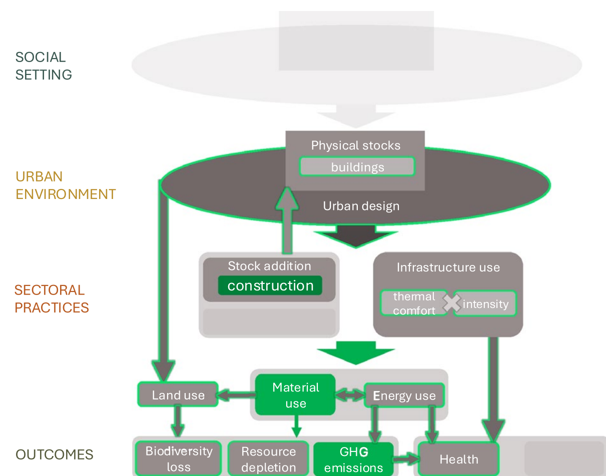
Floor area intensification



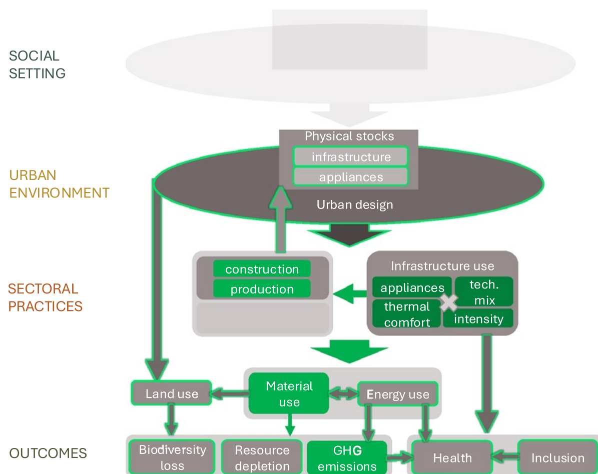
Repurposing obsolete infrastructure



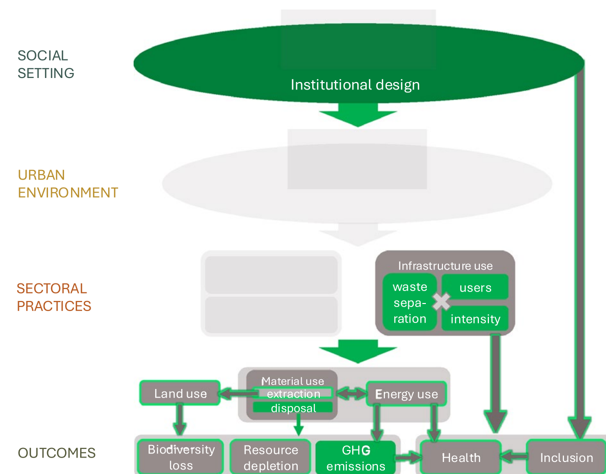
Material substitution



Electricity load shifting



Normative feedback for waste separation



Legend
leverage point → targeted effect → ancillary change

◂**Fig. 3** Dynamic effects of six different leverage points for circularity and GHG mitigation illustrated by the INTURC framework. From top to bottom in rows: (1) high-accessibility residential planning; (2) floor area intensification; (3) repurposing obsolete infrastructure; (4) material substitution; (5) electricity load shifting; (6) normative feedback for waste separation

2024). Similarly, carbon pricing to incentivize material substitution may increase overall construction cost (and with that housing prices) if not accompanied by a transition in builder's skills and knowledge, the availability of alternative construction materials, and updates of building standards (Lu et al., 2012).

Overall, the application of INTURC reveals that circularity strategies have impacts on diverse outcomes from equity to biodiversity for which the effect is mediated by urban and institutional design. Hence, the evaluation of these strategies should cover a broad range of outcomes and dynamics.

4.5 Barriers and enablers for salient scenarios

Next to a more comprehensive understanding of the potential effects of circularity strategies, the INTURC framework allows to identify barriers and enablers for efficient material, energy and land use (Table 3).

Barriers to the urban circularity levers include trends such as urban sprawl and increasing demand for housing driven by smaller household sizes, which exacerbate resource consumption and strains on infrastructure (Ellsworth-Krebs, 2020; Ivanova & Büchs, 2022). The transition to low-carbon construction and adaptive reuse of existing infrastructure remains hindered by entrenched practices and institutional inertia. Hence, an intensified use of existing buildings is highly dependent on changes in attitudes, norms and institutional design.

Institutional levers are key to mediating the adoption and scalability of circularity strategies. Urban circularity strategies require coordinated investments in infrastructure, robust regulations such as zoning laws, and targeted economic incentives. Measures that depend on behavior change at the household level such as electricity load shifting and waste separation require strong institutional design such as dynamic time-of-use electricity tariffs, normative feedback and flexible work hours. Zoning policies that reduce urban sprawl and promote proximity-based housing development exemplify the regulatory leverage needed. Projects like transit-oriented development in Curitiba highlight how infrastructure investments can integrate mobility and housing, reducing commuting times and improving quality of life. Similarly, economic incentives encouraging the adoption of sustainable construction materials, such as Amsterdam's mandate for timber in housing, showcase how policy can drive innovation while fostering a sense of community and ecological stewardship. Policy and regulation also play a role in mitigating potential gentrification effects of such neighborhood-improving projects (Turbay et al., 2024).

By embedding urban resource flows within a social setting, the INTURC framework allows to identify such dynamics that are important to consider for constructing plausible and salient scenarios and translating scenarios into practice.

4.6 Modelling urban circularity

INTURC facilitates the identification of relevant links to move towards "apples-to-apples" comparisons. Yet, to translate these links into modelling practice, an integration and further improvement of modelling tools is required. Existing models for urban circularity strategies capture individual interventions, but inconsistencies in accounting frameworks and boundary definitions hinder direct comparisons between outcomes. A summary of existing integrated models, as interpreted from this urban circularity angle, can be found in Supplementary Information SI1.

Technical and environmental assessments offer the potential for cross-impact assessments available through lifecycle impact assessment methodologies (LCIA) and cost–benefit analysis. Yet, they tend to focus on first order effects often neglecting cross-sector interactions and equity impacts at the systems level.

Spatial dynamic material flow models emerge as a promising variant of technical and environmental assessments which include cartesian understandings of spatiality and feed on available big data. Dynamic stock models can, for instance, be used to evaluate temporal (mis) match of material in- and outflows and determine the need for storage in circular construction hubs (Tsui et al., 2024). For comprehensive assessments, these also need to include cross-sector effects and future applications of the material which influence optimal location of storage and potential benefits (Desing et al., 2024). For a more comprehensive representation of spatiality that still allows for aggregate accounting, key urban form metrics such as the 5 Ds (density, diversity, distance, destination accessibility, design) could be incorporated as dimensions of integrated models.

The modelling of societal structure and institutional design requires some form of actor representation linking industrial ecology tools to behavioral models (Baumann & Lindkvist, 2022). Demand response models simulate energy consumption patterns but are typically isolated from other sectors, reducing their integrative utility. Agent-based models (ABMs) are widely used to simulate the impacts of policies and urban plans at the micro-level integrating aspects of urban and institutional design. These models excel

Table 1 Current estimates of the targeted effect of each leverage point

Leverage points	Description	Targeted effects	Effect size
High-accessibility residential planning	Densifying and locating new dwellings close to public transport and urban centers	Proximity to existing road and rail infrastructure reduces material use; shorter distances to transport and amenities lead to modal shifts, lower car ownership, and reduced energy use	2–3% less transport-related GHG emissions for the EU from 2025–2050 (Nachtigall et al., 2024) (EU DG Energy, 2024; Eurostat, 2025; Thomsen & Van der Flier, 2010)
Floor area intensification	Reutilizing unoccupied buildings, renovating and repurposing, and sharing spaces	Higher occupancy in existing buildings reduces new construction; increased local population density improves transport and amenities, reducing transport energy and emissions	Reutilizing unoccupied dwellings: 40% less construction for EU from 2025–2050. Moving into smaller dwellings: 3–4% per capita floor area reduction. Sharing space: 1–17% reduction in per capita floor area. (Eurostat, 2024a, 2025; Grubler et al., 2018; Heylen & Vanderstraeten, 2019; Millward-Hopkins et al., 2020; Pfnür et al., 2023; Thomsen & Van der Flier, 2010)
Repurposing obsolete infrastructure	Retrofitting obsolete gas pipelines for district heating	Using existing pipeline materials lowers the demand for new pipelines, reducing material extraction and production	up to 45% less GHG emissions per district heating pipe construction, around 8 Mt CO_2e savings, if 1/3 of existing gas pipelines in EU would get repurposed (Wiedmann, 2024)
Material substitution with low-carbon materials	Substituting high-carbon materials with bio-based alternatives	Bio-based materials reduce GHG emissions from construction material production	up to 50% less CO_2 emissions related to construction materials from 2020–2050 assuming 90% mass timber construction globally (Churkina et al., 2020)
Electricity load shifting	Optimizing electricity demand to align with renewable supply	Minimizing reliance on fossil fuels during peak hours, reducing grid and storage needs and related material and energy use, reducing energy costs	15% less GHG emission in the building sector by 2050 related to adaptive heating/cooling systems (IPCC, 2023)
Normative feedback for waste separation	Increasing feedback to improve household waste separation	Less unsorted waste reduces GHG emissions from incineration or landfill; material recovery lowers material extraction	6–7% reduction in volume of unsorted waste due to normative feedback based on field experiments in Italy and Sweden (Bonan et al., 2025; Ek & Söderberg, 2024)

Table 2 Synergies and trade-offs of the leverage points with human well-being and planetary stability

Leverage point	Key benefits	Key tradeoffs	Distributional effects
High-accessibility residential planning	Proximity to transport and destinations reduces GHG emissions (Nachtigall et al., 2024); modal shifts promote active mobility and health benefits (especially if complemented with green infrastructure)	Urban heat islands may reduce thermal comfort (Li et al., 2020); different demography attracted such as high-income earners with higher consumption (Ottelin et al., 2015, 2024); higher building density can impact mental health and well-being (Pont et al., 2021)	Increased access to low-cost mobility and basic services for resident low-income groups; potential gentrification along public transport routes (Turbay et al., 2024) requires safeguarding of housing prices
Floor area intensification	More people in existing buildings lowers need for new construction; sharing space reduces per capita energy and resource use; cohousing can reduce loneliness (Carrere et al., 2020)	Higher population density may increase noise and air pollution exposure (Pont et al., 2021); mental health impacts from reduced privacy in shared spaces	Floor area caps or taxation can promote more equitable space distribution; cohousing can reduce individual cost of living
Repurposing obsolete infrastructure	Using existing pipelines reduces material use and construction energy; faster rollout of low-carbon heating access	Decommissioning obsolete infrastructure incurs upfront costs but may save public funds in the long run	More equitable access to low-carbon heating, especially for multifamily households
Material substitution with low-carbon materials	Replacing high-carbon materials lowers GHG emissions at low transition cost	New material supply chains may alter local biodiversity and pollution dynamics	Carbon pricing may increase construction costs, potentially raising living costs
Normative feedback for waste separation	Increased waste separation reduces landfill and incineration emissions; energy recovery through recycling	More waste separation may increase energy use for recycling	Waste pricing mechanisms can impact equity, but information feedback on waste bills and volume can amplify waste separation without further increase in prices
Electricity load shifting	Shifting energy use to renewable production times reduces fossil fuel dependency; lowers peak demand infrastructure costs	High upfront costs for smart appliances and storage; changes in user behavior require skills and flexibility capital	Reduced energy costs for users who adopt practices; risk of excluding vulnerable groups due to high upfront costs; households with children or elderly may face challenges in adopting load-shifting practices

Table 3 Enablers and barriers in current trends of implementing the urban circularity leverage points

Leverage point	Trend without intervention	Implementation mechanisms	Examples
High-accessibility residential planning	New dwellings are often in low-density outskirts, leading to higher transport-related GHG emissions	Zoning policies, transit-oriented development, and public transport investments	Transit-oriented development in Curitiba (Brazil), Arlington (US), and Toronto (Canada) (ICLEI, 2016)
Floor area intensification	Smaller households increase per capita dwelling size; urbanization leaves rural dwellings underutilized; new homes become larger	Rent caps, matchmaking for underutilized dwellings, floor area regulation, economic revitalization, and heritage promotion	Matchmaking in Baden-Württemberg (Germany), Test-housing in Görlitz (Germany), Portmeirion (Wales) (Städtetag Baden-Württemberg, 2022; Zöllter et al., 2024)
Repurposing obsolete infrastructure	Gas pipelines become obsolete due to carbon pricing and district heating replacement	Green procurement, carbon pricing, resource royalties, and legal obligations to remove obsolete assets	Coal power stations repurposed for manufacturing of housing in Page, Arizona (US) (Allen, 2022)
Material substitution with low-carbon materials	High-carbon materials remain dominant despite innovations in lightweighting and wood construction	Building codes, green procurement, carbon pricing, and financial incentives for low-carbon materials	Wood construction legacy in Finland, Sweden and Norway; 20% wood construction requirement in Amsterdam (Netherlands) (Metropolitan Area of Amsterdam, 2025)
Electricity load shifting	Higher energy consumption peaks strain the grid, need for more peak power plants, increasing fossil fuel reliance and underutilizing renewable energy	Smart meter rollout, subsidies for energy-related smart home devices, virtual power plants (VPP), demand-side management (DSM), and dynamic electricity tariffs	Night storage heaters in the UK, households connected to virtual power plants in Australia and Italy, demand-side management in South Korea
Normative feedback for waste separation	Limited waste separation increases landfill and incineration emissions; energy-intensive recycling systems are underutilized	Waste cap pricing schemes, normative feedback mechanisms, and educational campaigns	Field experiment with normative feedback in Ferrara (Italy) and two municipalities in Sweden

at capturing individual behaviors and decision-making processes but often rely on exogenous normative assumptions, including on preference heterogeneity and the influence of interpersonal interaction. This limits their applicability across diverse urban contexts.

To improve consistency and comparability, integrated models are needed that combine dynamic assessments of material stocks and flows with regional demographic projections. Multi-agent models, for instance, can simulate the complex interactions between individual behavior, urban infrastructure, and policy interventions over longer time horizons. Similarly, dynamic traffic forecasting and localized demographic studies could provide insights into sectoral interactions and long-term impacts. In practice, we expect the application of INTURC as a pre-modelling screening tool to motivate the collection of geolocated, behavior response and socially stratified data alongside standard metrics such as aggregate material flows. Aligning methodologies and expanding boundary definitions, in turn, results in more comprehensive evaluations and better comparisons across urban circularity strategies.

Unlike the above-mentioned modeling approaches, and as a unique feature, INTURC supports the prioritization of high-impact, near-term strategies by explicitly integrating spatial form, material stocks, and institutional dynamics. Whereas existing models often lack spatial resolution or neglect behavioral adoption and policy responsiveness, INTURC links design levers—such as floor area intensification or infrastructure reuse—with socio-institutional mechanisms like zoning or normative feedback, enabling spatially contextualized and temporally actionable insights.

Time especially matters given the urgency of the planetary crisis which increases the importance of reducing upfront emissions embodied in materials used for construction of buildings and infrastructure (Röck et al., 2020). Circularity has the potential to accelerate the transformation of urban spaces, leading to a systemic reduction in cumulative impacts far greater than an isolated analysis may suggest (Desing & Widmer, 2022). Thus, the identification of leverage points and related interventions with the INTURC framework also requires considering the different speeds at which each of the components act (Table 4). For instance, a change in information feedback might trigger immediate changes in infrastructure use, whereas a change in urban form of buildings will take years or decades to materialize (Otto et al., 2020). The modular structure of the INTURC framework allows to capture both fast-acting and slow-changing dynamics, helping to distinguish which strategies (e.g., load shifting vs. material substitution) are more viable under current urban and governance constraints.

To employ INTURC as a pre-modelling screening tool, we recommend consulting the framework right after the definition of the research goal and target strategy: Locate the circularity strategy in the diagram (Fig. 1) and identify any relevant influencing factors or outcomes as demonstrated with Fig. 3; then consider whether you can represent these factors and outcomes with your model or contextualize your findings. Similarly, the framework can also be used to identify levers and side-effects in urban policy practice that aims at advancing circularity. Thus, INTURC serves both as a starting point for new models and adjusting and extending existing models (see Table 4), but also as operational guide for prioritizing decisions in municipalities.

5 Discussion and conclusion: applying INTURC to improve urban circularity modelling

The state-of-the-art for understanding urban circularity is still largely based on sector-specific perspectives that draw on material accounting methods from industrial ecology applied to urban metabolisms. This has four main limitations. First, cross-sectoral and systemic effects can be missed. Second, spatial dimensions and the importance of urban form and design are sidelined. Third, inconsistent system boundaries used in modelling analyses prevent comparability and generalizable insights. Fourth, quantified impacts on materials, energy, and GHG emissions are not linked to well-being outcomes necessary for informed trade-off analysis of circularity strategies. Tackling these limitations requires an integrated operational framework and modelling approaches derived from it. With the INTURC framework we provide the basis for such an integrated perspective.

We highlight three insights drawn from the application of INTURC, related to identifying cross-sectoral synergies, the relevance of institutional design for circularity, and the importance for spatial embeddedness in the urban context.

Floor area intensification and spatial planning can yield the strongest cross-sectoral synergies among urban circularity strategies. As detailed in Sects. 4.2 and 4.3, intensifying use of existing building stock reduces demand for new construction materials (Table 1), while simultaneously lowering per capita energy use and enabling more efficient transport through increased local density. These material savings are coupled with synergies for well-being, such as reduced commuting distances and enhanced social connectivity through cohousing models (Table 2). When embedded in high-accessibility urban forms—such as transit-oriented development—these strategies amplify their systemic impact by integrating urban design with behavioral shifts in dwelling use, demonstrating how the INTURC framework identifies priority interventions at the intersection of physical infrastructure and social practice.

Table 4 Current and suggested modelling practices for an integrated representation of circularity strategies and their dynamic effect

Leverage point	Current modeling approaches	Suggestions for improved modeling	Example improvements to existing models	Time scales involved
High-accessibility residential planning	Agent-based modeling for policy and planning impacts; graph neural networks for traffic forecasts	Long-term traffic forecasts incorporating socio-economic factors; causal modeling of policy effects on transport and emissions trade-offs	Integrating transport infrastructure and building material requirements as quantified by spatial material stock analysis (Wiedenhofer et al., 2024a, 2024b) in models analyzing transport energy savings of urban form (Nachtigall et al., 2024)	Generational (30–100 year) changes in road layouts and total building stock composition Several years (1–5 years) from plan to construction for vertical extension and infill of buildings
Floor area intensification	Assumptions on per capita floor area reductions and material efficiency in using vs. preserving vacant buildings	Regional demographic projections, geospatial modeling of future dwelling preferences, and integrated assessment of urban–rural dynamics, representing mechanisms of place-based policies on stock usage	Integrating un(der)occupied stock (Lage et al., 2024) together with location-dependent transport demand (Berrill et al., 2024; Nachtigall et al., 2024) in housing models	Generational (30–100 year) changes in total building stock composition and household size trend 1–2 years to split existing housing units or repurpose non-residential buildings for residential use Life course events shape housing situations at the individual level
Repurposing obsolete infrastructure	Life cycle assessments (LCA) comparing circular alternatives like repurposing pipelines for district heating	Dynamic material stock-flow modeling linked to services and supply constraints; policy-focused economic modeling	Comparing different application scenarios for materials from the urban mine in consequential LCAs (Desing et al. 2024)	Several months from urban mining to new application requires storage space Several years between individual road openings for maintenance Phase out target years moderate demand for new infrastructure
Material substitution with low-carbon materials	LCAs of alternative building materials such as biochar or wood construction	Dynamic assessment of material stocks and flows, including service impacts and economic policy implications	Integrating forest management (Daigneault et al., 2022) with construction sector scenarios (Mastrucci et al., 2024) in shared socio-economic pathways	Application of different materials requires change in professional skills requiring updated curricula and retraining Decadal changes in standards and regulation for construction sector Supply of timber depends on plantation decisions decades earlier
Electricity load shifting	Demand response modeling, agent-based modeling, and LCA of emissions avoided during off-peak renewable use	Multi-agent models for consumer behavioral responses to dynamic pricing; artificial intelligence-driven optimization with smart grid, urban stock, and electric vehicle infrastructure data	Integrating demand response behavior to policies (Khanna et al., 2021) in coupled energy-material-land system models (Vivier et al., 2025)	Price feedbacks can change behavior in weeks to months if information available Dynamic pricing with smart meters can change demand hourly Decadal changes in grid infrastructure capacity in type
Normative feedback for waste separation	Limited integration of behavioral and normative aspects in current models	Models incorporating pricing mechanisms, feedback systems, and behavioral economics to simulate waste reduction and recycling impacts	Assessing equity together with environmental outcomes in comparing policy options for waste reduction (Bonan et al., 2025)	Normative feedback can change behavior in weeks to months with sufficient information available Separate waste collection rollout possible within months to years

The scaling and distributional effects of circularity strategies hinge on institutional design. As outlined in Sect. 4.4, interventions like dynamic electricity tariffs for load shifting, rent regulation for shared housing, or normative feedback for waste separation are only effective when aligned with enabling regulations and socio-political acceptance. Without zoning reforms or incentives, floor area intensification risks exacerbating housing inequality or displacement (Table 2). Likewise, material substitution may raise construction costs unless procurement policies, vocational training and building codes are adapted. INTURC reveals that technical strategies often depend on institutional scaffolding for uptake, while also shaping who benefits from circularity transitions. Effective governance mechanisms are thus not merely complementary—they are constitutive of successful circularity interventions.

Spatial embeddedness is a necessary condition for realizing the full systemic benefits of circularity strategies. As shown across multiple leverage points (Sects. 4.2 and 4.5), strategies like repurposing obsolete gas pipelines or desealing surfaces yield environmental gains only when spatial relationships—such as proximity between resource and reuse site—are optimized. Similarly, electricity load shifting is more impactful when integrated with localized renewable generation and storage infrastructure. INTURC highlights these spatial contingencies: interventions must be matched to urban form and geographic conditions to avoid unintended rebounds. For example, densified housing without adequate green buffers may worsen urban heat islands or degrade quality of life, undermining well-being goals (Table 2). The spatial character of INTURC enables prioritizing strategies where material, infrastructural, and behavioral efficiencies align.

INTURC can guide urban circularity modelling. INTURC integrates cross-sectoral dynamics and multi-scale feedback into a spatially explicit framework, linking existing tools such as material flow analysis, urban metabolism models, and spatial life cycle assessments. It enables coupling of upstream and downstream subsystems—for example, connecting urban energy demand models with transport simulations to assess how high-density residential planning affects both mobility emissions and infrastructure needs. Similarly, it extends waste management models to include reuse effects in construction and manufacturing. By incorporating geospatial data and urban form characteristics, INTURC supports spatialized mapping of material stocks and flows, which can guide cities in prioritizing areas for infrastructure reuse, adaptive retrofitting, and zoning reforms.

Yet, INTURC becomes particularly relevant in devising circularity approaches tailored to local conditions by also highlighting the social and institutional dynamics at play. INTURC links agent-based or system-dynamics models with insights on financial incentives, regulatory structures, and adoption barriers—such as using behavioral data to improve models for electricity load shifting or travel behavior. This integration reveals trade-offs in urban design, such as how compact forms lower GHG emissions but may intensify urban heat or strain public services. We hereby address and go beyond the call by Schiller et al. (2025) for operational frameworks that integrate aspects of spatial design to enable consistent comparisons across strategies and sectors within harmonized boundary conditions.

INTURC thus supports policy-relevant modeling across resource, infrastructure, and human domains. To operationalize it, the authors recommend open-source modular platforms, harmonized data boundaries, and application to diverse real-world case studies to enhance consistency and cross-context learning, including in integrated assessment model modules such as MESSAGEix-Buildings and MESSAGEix-Transport (Krey et al., 2020; Mastrucci et al., 2021). The collection of geolocated, behavior response and socially stratified data alongside aggregate material flows will be crucial to realize this potential. In this way, we hope that INTURC can shift urban circularity modelling from fragmented sectoral analyses to an integrated approach capable of supporting the sustainable transformation of our cities.

6 Summaries:

Supplementary Information SI1: This supplementary information provides an additional graphical interpretation of existing models using the Integrated Urban Circularity framework.

Supplementary Information SI2: This supplementary information contains further definitions of constructs and explanations of relations included in the Integrated Urban Circularity framework.

Supplementary Information SI3: This supplementary information contains further explanation of the selection criteria for the case studies.

Supplementary Information SI4: This supplementary information contains the assessment underlying Figure 2.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44498-026-00108-x.

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Declarations

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