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Research article

How ex ante policy evaluation supports circular city development: Amsterdam's mass timber construction policy

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ABSTRACT

This article aimed to assess the potential impact of policy actions to support mass timber construction through an ex ante policy analysis in Amsterdam. Through a combination of policy coherence analysis and agent-based simulation, the study evaluates 130 policy actions, including 80 specific instruments, for the transition from traditional masonry to mass timber construction. The coherence analysis reveals a predominance of regulatory instruments (62%) and a lack of active economic measures (16%), which limits their impact on circular city development. The simulation tested three instruments - demolition notification, a mass timber subsidy proxy and a carbon tax proxy - to assess their individual and combined effectiveness. Isolated measures, such as material price adjustments, were found to be insufficient due to systemic inertia. However, the combination of subsidies and carbon taxes proves more effective, significantly increasing the uptake of mass timber construction as its cost is reduced and construction companies develop expertise. A key finding highlights the complementary role of recycled concrete in supporting mass timber construction, highlighting the need for integrated policies targeting both mass timber and secondary materials. Improving industry knowledge and expertise is identified as a transformative approach to reducing costs and overcoming barriers to adoption. This research is the first contribution to demonstrate the value of ex ante policy evaluation and agent-based simulation in formulating coherent and effective policies for circular city transitions. Policy makers in Amsterdam and other Dutch cities are advised to implement synergistic instruments, support local material reuse and invest in capacity building to achieve carbon neutrality and resource circularity in urban construction. The findings provide actionable guidance for Amsterdam and similar cities seeking to promote sustainable and circular urban environments.

1. Introduction

Mass timber buildings are gaining attention from among policy makers as these buildings align carbon neutrality and circular economy goals to address unsustainable patterns of urbanisation (UNEP, 2023). Firstly, mass timber, or the group of engineered wood products resulting from the aggregation of smaller wood elements, is one of the most prominent alternatives to conventional building materials in reducing carbon emissions (Buchanan and Levine, 1999; Churkina et al., 2020; Gustavsson and Sathre, 2011; Pajchrowski et al., 2014). Substituting today's conventional building materials, such as concrete and steel, with mass timber could reduce carbon emission up to 69% in the construction phase, as well as contribute to a potential 9% reduction of global carbon emissions by 2030 (Himes and Busby, 2020). Second, mass timber holds the promise of achieving a circular built environment, because it integrates circular building strategies such as modular design, design for disassembly, the reuse of components (e.g., walls, windows) rather than recycling of materials (e.g., timber, glass). In short, mass timber construction supports the upcycling of building components, thus potentially extending the life of building materials and reducing the use of new raw materials and the generation of waste and emissions from the construction sector (Ghobadi and Sepasgozar, 2023).

Circular cities are "*complex urban systems in which resources are looped, the ecosystem is regenerated and the socio-technical systems*

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(infrastructure and communities) evolve with changing context" (Williams, 2021, p. 158). One of the aims of a circular city is thus to reduce the use of non-renewable resources such as energy and materials, which, in turn, reduces waste and emissions, steering clear of the linear "make--use-waste" model of urban development (Paiho et al., 2020; Williams, 2019, 2021). Therefore, mass timber construction aligns with the development of circular cities as it can enable resource looping through the reuse of building components, can contribute to more regenerative practices through sustainable forestry practices, and meet future needs through infrastructure and building adaptation by modular construction. While promising and contributing to achieve two important ongoing urban policy goals around the world, namely circularity and carbon neutrality (UNEP, 2023), the adoption of mass timber construction has been rather slow in countries that have promoted its use since the 2010s (Franzini et al., 2018); doubts about its fire resistance, competitiveness, price, and durability are among the main reasons (Ghobadi and Sepasgozar, 2023). From a carbon accounting perspective, a recent article and report by Peng et al. (2023) and the World Resource Institute (2023) have critiqued the current and future status of the mass timber resource base, pointing out that (1) wood harvesting has negative consequences for carbon emission reduction, (2) most of the wood and its stored carbon is lost during production, and harvesting wood is not carbon neutral, and (3) the use of wood in construction will most likely increase climate warming for decades. These critiques highlight that the potential positive climate impacts of mass timber construction depend on the resource base (e.g. how, where, and what timber is produced) and not only on the circular use of mass timber.

This article focuses on the role of policy actions in achieving the uptake of mass timber construction. While policies to promote timber construction in cities are increasingly being adopted, an important explanation for the achievement of these policy goals lies in the policy actions through which policies are implemented (Bemelmans-Videc et al., 2003; Howlett et al., 2020). Different policy actions could incentivise timber construction in European cities. Indirectly, timber construction can be promoted by reducing environmentally damaging resource use, for example, through climate and product policies. Directly, policies can support timber construction processes and products as well as naturally occurring materials, or the resource base (e.g. supply-push policies) (Hildebrandt et al., 2017). To date, mass timber has only indirectly become a policy option to reduce construction emissions at the European level (EC, 2021) and only secondarily to the need to protect and enhance forests across the region for carbon removal (European Council, 2023). In 2010, there were no policy actions directly supporting timber construction at the European level, but also no formal barriers to the increased use of timber in construction (Tykkä et al., 2010). This context remains in 2022. The "Fit for 55" climate package adopted by the European Union (EU) includes policy instruments that directly affect forest management and timber production, i.e. the New EU Forest Strategy for 2030, the EU Renewable Energy Directive, and the Regulation on Land Use, Land Use Change and Forestry. However, these policy instruments do not directly promote timber construction (EC, 2021).

One of the European cities that has set a policy objective to achieve timber construction is the Dutch city of Amsterdam, especially with its Green Deal Timber Construction (Metropoolregio Amsterdam, 2021), a multi-actor agreement to support mass timber construction with the goal of incorporating at least 20% of timber in new build by 2025. This agreement signed by key stakeholders in the building sector follows the long-term policy objective to transition to a more circular city and a decade of circular city policy development (Gemeente Amsterdam, 2020). Amsterdam provides an excellent case study to examine the effect of policy actions for mass timber constructions. The Netherlands Environmental Assessment Agency (PBL) concluded that ill-equipped circular economy (CE) policies in the Netherlands must be provisioned with more forcible instruments (i.e. regulations, standards, economic stimuli) (cf. PBL, 2021). All in all, the status of the circular city policies in Amsterdam can be categorized as driven by economic development and lacking policy actions in relation to the built environment, spatial planning, and the inclusion of nature based solutions, a situation that could affect the effectiveness of such policies (Calisto Friant et al., 2023). Further at the European level, CE policy instruments have proven ineffective. More than €10 billion worth of economic stimuli designed to incentive CE innovation and adoption were ineffectively deployed to solve waste management issues (European Court of Auditors, 2023). Arguably, ineffective CE policies can be linked to a lack of policy coherence: the (mis)alignment and synergies between policy objectives, instruments and implementation practices (Trencher and van der Heijden, 2019). Informing policy makers about the most effective ways to design policy instruments and their mix has been identified as a way forward in CE policy instrument research (Deserno and Sterk, 2024).

Given the scale of the built environment, any policy aimed at change is, in principle, a long-term policy, and given the current state of circular city policy in Amsterdam, ex post policy evaluation, the dominant form of policy evaluation that takes place after a policy has been implemented (cf. Howlett et al., 2020; Wollmann, 2009), is not useful for assessing the effectiveness of policy actions in relation to timber construction in Amsterdam. Instead, ex ante policy evaluation, aimed to hypothetically anticipate the effects and consequences of policy actions by means of the analysis of chosen policy objectives and instruments, might inform policy formulation and improve the effectiveness of recently emerged policies for mass timber construction (Boero, 2015; Wollmann, 2009). Hence, this article poses the following two research questions: *How coherent are policy actions for mass timber construction in Amsterdam?* and *how can* ex ante *policy evaluation inform policy formulation for mass timber construction in Amsterdam?*

The aim of this article is to assess the potential effect of policy actions in support of mass timber construction by means of *ex* ante policy analysis in Amsterdam. The paper is structured as follows. The next section presents the theoretical framework based on policy formulation and ex ante policy evaluation. The methods and materials used in this article are then explained. The results are presented in relation to the coherence and ex ante evaluation of policy measures for construction in Amsterdam. Finally, discussions and conclusions are presented in relation to the research questions of this article.

2. Background

2.1. Policy formulation and evaluation

Public policy can be understood as a set of interrelated decisions taken by political actors to select objectives and the means to achieve them (actions) within the limits of their authority (Jenkins, 1978). Policies are usually studied and to some extent developed according to the so-called policy cycle or process, which includes five stages: (i) agenda setting, which refers to how problems are brought to the attention of government; (ii) policy formulation, that involves the development of policy options within government; (iii) decision making, which is the process by which governments choose a course of action or inaction; (iv) policy implementation, that refers to the implementation of policies; and (v) evaluation, which involves monitoring and assessing outcomes, possibly leading to revisions in policy problems and solutions (cf. Howlett et al., 2020; Jann and Wegrich, 2017; Yu et al., 2022).

For this article, formulation and evaluation are of particular interest as they deal with the selection of policy actions and their evaluation at the end of the policy cycle. Formulation and evaluation differ from the other stages in the policy cycle in that they are 'backroom functions' (Fischer et al., 2007), which refers to more technical processes that often involve fewer people than agenda-setting, decision-making, and implementation. Policy formulation aims to translate policy objectives into concrete actions and demonstrable results (Bemelmans-Videc et al., 2003), these actions are in many cases concrete policy instruments[1] that can be divided into three generic types: regulatory (e.g. laws, regulations, standards), economic (e.g. subsidies, grants, taxes), and information (e.g. guidelines, information systems, awareness campaigns) (Vedung, 1998). In some other cases, policy actions involve the willingness or commitment of political actors to make progress in certain directions (expected instruments) in the future, for example, a commitment to legislate in the future about a certain matter as part of a broader set of policy actions and instruments. This article resorts to the concept of policy actions.

Policy evaluation is a formal or informal retrospective (ex post) assessment process of policy outputs and outcomes, which is carried out after the implementation of the policy so to determine whether the policy objectives were achieved. The evaluation normally comprises either the assessment of the policy *processes* by means of inputs and outputs, which is meant to provide relevant information for the implementation phase (Wollmann, 2009), or *impacts* based on the effects of the policy (Howlett et al., 2020).

On this basis, circular city policies have started to gain attention regarding their formulation and evaluation. Although research on circular cities has grown rapidly since 2015 (Bucci Ancapi et al., 2022a), its governance aspects have only recently been addressed. Amsterdam has been of special interest for research as the city has developed circular city policies over a decade. According to Williams (2023), Amsterdam has adopted a city-wide circular tendering policy to promote circular city development, resulting in new circular building networks for the use of recycled concrete and modular construction, and the demonstration of circular building methods. Other actions have integrated circular principles in the built environment, namely, (i) high value reuse and recycling, (ii) smart design, (iii) resource exchange, and (iv) improved separation of waste streams (Williams, 2021). While Amsterdam has advanced circular city policies, these policies have also been criticised given their narrow economic focus. According to Calisto Friant et al. (2023), circular city policies in Amsterdam focus on economic competitiveness and technological innovation but overlook its social, political, and ecological implications. Indeed, their findings highlight main areas of policy development: governance and municipal operations, food and organic waste streams, and education and knowledge development. On the contrary, the built environment and territorial planning, ecosystems and nature based solutions, and renewable energy are the least development areas. Specifically on the analysis of circular city policies, Bucci Ancapi (2023) developed a circular city policy coherence framework to analyse the (mis)alignment of policy objectives, instruments, and implementation practices in the transition towards circular cities (Fig. 1). The use of the circular city policy coherence framework identified a similar trend in circular built environment policies at the national level in the Netherlands, where most policies are equipped to foster circular supply-chains in the built environment, but not necessarily contributing to the development of a circular city. Additionally, the analysis of circular built environment policies in the Netherlands showed the lack of consistent set of policy instruments to facilitate the transition (e.g. regulations, material passports, market formation, and economic stimuli) (Bucci Ancapi, 2023). The Circular city policy coherence analysis framework was recently used to analyse the coherence of circular built environment policies in Greater London, which also found a predominance of economic growth and resource recycling policies over environmental regeneration and adaptation policies (Bucci Ancapi et al., 2024).

2.2. *Ex ante policy (instrument) evaluation*

Another category of public policy evaluation has been developed in conjunction with the development of computer simulations: ex ante evaluation (Boero et al., 2015). In contrast to ex post evaluation, ex ante evaluation is carried out before a policy is implemented. Its purpose is to support policy formulation or the choice and design of policy objectives and instruments and to (possibly) anticipate and pre-assess a policy's effects and consequences (Howlett et al., 2020; Wollmann, 2009). According to Boero (2015), two issues in policy formulation make ex ante evaluation useful, at least scientifically, let alone its convenience to explore the robustness of public policy, namely: (1) easy enthusiasm for a policy choice and (2) addressing issues that have recently emerged. The first issue has to do with policy choices that are gaining support at rapid pace, the consequences of which may seem whimsical and the possible outcomes of which are not properly understood. The second, which is of central interest to this paper, has to do with emerging issues for which knowledge is not sufficiently collected or developed; for example, the circular economy (cf. Kirchherr et al., 2023; Korhonen et al., 2018).

Computer simulations, such as those performed through Agent-Based Simulation (ABS), have facilitated the study of complex systems in many policy areas, including the built environment (Gaudiano, 2013; Meadows et al., 1972; Portugali et al., 2012). ABS is a computer-based modelling approach used to represent, compute, and explore the effects of complex assumptions of relations between social actors and the systems they are embedded in (Ghorbani et al., 2014; Zellner, 2008). These models make use of both structural data (i.e. data that specifies the model structure and functioning) and emergent data (i.e. data resulting from running the model that accounts for the behaviour of a system as a whole) (Gaudiano, 2013). ABS develops object-oriented computer programs, wherein objects are actors making rule-based decisions in an environment that is also modelled. Both actors and the environment possess specific attributes that condition their overall behaviour in the system. For instance, in the built environment, actors can be building owners, developers, demolition companies, among others. The built environment (the model's environment) can be featured with different building typologies and parameters (Gaudiano, 2013).

ABS is used in ex ante policy evaluation. As ABS are usually based on rule-based decisions (just like policy instruments), they are particularly useful for describing how agents with different information, decision rules, and unpredictable situations interact with each other and what the outcomes of such interactions might be (González-Méndez et al., 2021; Lempert, 2002). ABS is useful to test the effect of specific policy actions in target groups, and convenient for *ex* ante policy evaluation when such experiment are costly or risky in real life (i.e. subsidies, taxes, zoning) (Epstein, 1999; Zellner, 2008). A major benefit of ABS is that they can provide policy and behavioural recommendations to political actors in anticipation of the plausible outcomes of their decisions, provided that an appropriate institutional framework is in place. ABS can also can also provide visualization tools for policymakers in collaborative learning activities (Zellner, 2008), improving policy in areas where multidisciplinary knowledge is required and divergent interest may affect policy outcomes (Savin et al., 2023). ABS can also help policymaking by providing quantitative support to policy stakeholders (Lempert, 2002). The main limitations of ABS lie on its predictive power, the result variability of the same parameters when the model is repeated, and the dependency on the model's assumptions (Manzo, 2014; Zellner, 2008). However, this limitation is also a result of misconception, for it is not the aim of ABS to provide recipes for action. Instead, the advantage of modelling actor-environment interactions resides in allowing the understanding of a wide range of emergent relationships through parametric variables that would be otherwise difficult to obtain (Epstein, 2008; González-Méndez et al., 2021). In other words, ABS can unveil the complexity embedded in the modelled actor-environment system, be informative on how actions might work out, and possibly deliver ex ante evaluation of actions. Specifically for the CE, Walzberg et al. (2023) can help model individual behaviour and stakeholder heterogeneity

[1] Also known as policy tools or governing instruments.

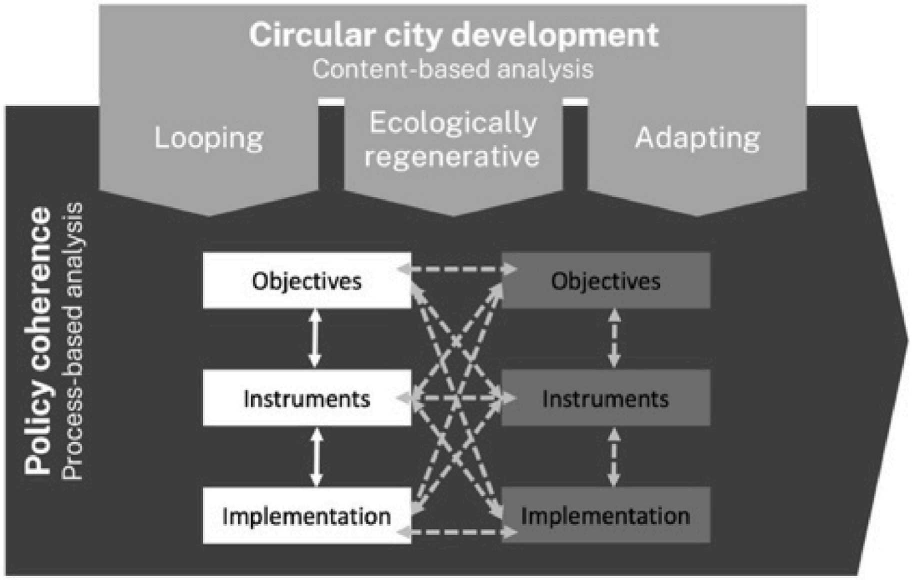

Fig. 1. Circular city policy coherence framework. *Source*: Bucci Ancapi (2023). **Note:** looping actions, akin to the 'R-Ladder' concept (Potting et al., 2017), involve reuse, recycling, and reduction strategies; ecologically regenerative actions aim at restoring ecosystems affected by unsustainable urbanization, for example through blue and green infrastructure and urban ecosystem services provision; and adapting actions focus on enhancing capacity-building and resilience to changing conditions across urban communities (Williams, 2019).

associated with increased circularity, as well as accounting for externalities associated with CE activities. Despite the potential benefits of using ABS in CE research, a recent systematic literature review highlights the minimal exploration of ABS for CE policy evaluation and the construction sector in particular (Rizzati and Landoni, 2024).

3. Materials & methods

This article explores ex ante evaluation of policy actions in support of mass timber construction in Amsterdam. After a preliminary review of policies for mass timber construction in Amsterdam it was decided to focus on policy actions rather than only on instruments, as many policy choices consider less defined actions to be implemented in the future instead of well-defined instruments (i.e. regulatory, economic and information) (Capano, 2023).

3.1. Coherence analysis of policy actions

Firstly, a coherence analysis of policy actions was conducted using the Circular city policy coherence framework by Bucci Ancapi (2023) to assess how aligned they are regarding circular city development. For this purpose, policy actions were gathered from three sources: Amsterdam Metropolitan Region's (AMR) documents 'Green Deal Timber Construction' (Metropoolregio Amsterdam, 2021), the 'Opportunities for financial incentives for timber construction' (Haisma, 2021), and the CircuLaw database on policy instruments for mass timber construction in Amsterdam (CircuLaw, 2023). CircuLaw is a City of Amsterdam initiative for the analysis and dissemination of existing regulatory instruments that can be used for circular economy purposes such as mass timber construction. All policy actions identified were classified according to the following criteria (Table 1). Three criteria were selected to contextualise the policy actions regarding their governance, namely, 'governance level', 'status' and 'regime'. 'Governance level' refers to the administrative boundary of application (i.e., municipal, provincial, national). 'Status' refers to whether the action is in place or just planned. 'Regime' distinguishes between public or private-led actions. Other four criteria were derived from the Circular city policy coherence framework, namely, 'action type', 'circular actions', 'support actions', and 'R-Ladder'. 'Action type' classifies actions in relation to the typology of Vedung (1998) which distinguishes 'sticks' (regulatory instruments like laws, regulations, and standards), 'carrots' (economic instruments such as taxes and subsidies), and 'sermons' (information instruments such as guidelines and information systems). Only actions that explicitly refer to an instrument type were classified as such. For example, 'promotion of wood projects in the city' would not be classified as an instrument, whereas a 'subsidy for wood projects in the city' or 'design guidelines for mass timber construction' would be classified as economic and information types. Both 'circular actions' and 'support actions' are derived from the circular city development framework of Williams (2019). Finally, the 'R-Ladder' is a well-known hierarchy of circular strategies that moves from least circular interventions (i.e., R6 – Recovery of energy from materials through incineration) to utmost circular ones (i.e., R1 – Refuse, abandoning a product by making its use obsolete). Strategies R1, R2, R3 hold the most transformative potential in bringing about a more circular economy (RVO, 2020).

3.2. Agent-based simulation for policy instruments

As seen earlier, ABS is useful to test the effect of specific policy actions in target groups, and convenient for in-silico ex ante policy evaluation (Epstein, 1999; Zellner, 2008). A common choice of ABS platform is that of NetLogo (Wilensky, 1999). NetLogo has been used in copious studies of policies (Kravari and Bassiliades, 2015).

Hence, secondly an ABS was modelled using NetLogo for the ex ante evaluation of policy instruments for mass timber construction. The ABS includes the interaction of agents in the built environment (i.e. households, companies, housing associations, houses, material suppliers, demolition companies and construction companies) and the residential and commercial buildings of Amsterdam, including building-related parameters (i.e. material intensities, building distribution, floor area, recycling rates and ownership distribution). The full dataset for this model, including the source of all parameters and a full description of agent interactions and assumptions in the models, can be found in the code availability section of this article. To populate the model accurately, physical parameters of Amsterdam's buildings were quantified. While not a one-to-one spatial representation, the current building stock is assessed using relevant parameters to create a simplified and scalable model. A simplified model is suitable for this ABS given the

Table 1
Criteria for policy instrument classification.

Governance level	Local	Provincial	National			
Status	Active	Inactive				
Regime	Public	Private				
Action type	Regulatory	Economic	Information			
Circular actions	Loop	Adapt	Ecological regeneration			
Support actions	Substitution	Optimisation	Localisation	Share		
R-Ladder	R6 - Recover	R5 - Recycle	R4 - Repair	R3 – Re-use	R2 - Reduce	R1 - Refuse

computational intensity of a real-scale model and given the purpose of this paper to only illustrate the usefulness of ABS in ex ante policy evaluation.

The NetLogo model consists of patches on a 2D grid representing residential or commercial buildings, such as apartments, houses, shops, and offices (N = 6835) (Statistics Netherlands, 2023b). Specifically, the 2D grid visualization does not reflect real spatial layout, with buildings randomly placed. Grid size does not correspond to real-world dimensions. Subcategories enable detailed data on construction years, floor surfaces, and material intensities. The model relies on a Weibull distribution for its accurate performance in material flow analysis, resulting in a mean lifespan of 63 years (Deetman et al., 2020). Material intensity derived from a material flow model of the Dutch city of Leiden (Yang et al., 2022), as this research did not count with material intensities[2] for the city of Amsterdam. This model assumes Amsterdam buildings use masonry initially and resorts to the estimation on material intensity for masonry buildings in the Netherlands by Sprecher et al. (2022) and an estimation for timber buildings derived from a construction portfolio by Smith and Wallwork Engineers (2023) as data on timber buildings is scarce. Few mass timber buildings exist in the city (Metropoolregio Amsterdam, 2023), at the time the study was done.

In the Netherlands, 95% of building demolition waste is recycled, mainly for low-value applications like road construction, and less than 3% of secondary materials are re-used in building construction (Schut et al., 2016). End-of-life collection rate was estimated at 85% for concrete and 95% for timber, while the recycled content potential was estimated at 50% for concrete and 90% for timber (Verhagen et al., 2021). From all construction and demolition waste in the Netherlands, concrete and masonry materials account for 64% and wood accounts for 6%; most concrete (78%) is downcycled as road base material and most wood (76%) incinerated (Zhang et al., 2020). An important limitation of the model lies in not including building renovation processes and a primary focus on new construction. This is due to the difficulty in modelling the work of renovation companies and the re-use of small, tailored wood components.

Construction costs between masonry and mass timber buildings vary and depend on builders' expertise with materials. For this study, material and labour costs were included as construction costs. A mass building is estimated as +35% in relation to a masonry one in the Netherlands (Beijers, 2021). Labour costs were also estimated at 55% of total construction costs (Shet and Narwade, 2016; Statistics Netherlands, 2023b; Vipin and Rahima Shabeen, 2019). Costs of material, cost per square metre constructed and the ratio of material cost as a percentage of total construction were calculated, which allowed to determine a learning rate for construction using Wright's Law or Learning Curve Effect $C(N) = C_1 N^{-\beta}$ (Mályusz and Varga, 2017).

Agents in the model use an asynchronous messaging system to communicate construction and demolition instructions, invoices, and other relevant information. Each agent has an inbox and an outbox, systematically processing messages and taking appropriate actions. Messages are then moved to the outbox for transmission to relevant agents, facilitating ongoing communication throughout the simulation.

With each iteration, the model proceeds as follows (Fig. 2). Owners assess their building stock, initiating demolition, and construction cost requests, while also reviewing construction estimates and forwarding commissions to architecture and construction companies. Construction companies handle material cost requests, manage projects, and send construction cost estimates to owners. They subsequently update construction time and parameters, and remove completed projects. The demolition company adds projects, dispatches secondary materials to the supplier, and updates demolition parameters, then to remove completed projects. The demolition company then clears material stock and sends a secondary material request to the supplier. The material supplier calculates material costs, sends responses to construction and demolition companies, and updates material stock. The model checks for messages in outboxes, sending them from sender's outbox to receiver's inbox.

The model underwent rigorous verification to ensure its validity and the reliability of policy findings. This process included aligning the model description with its actual implementation, conducting a code review, testing boundaries, checking for consistency, analysing step-by-step behaviour, and performing a global sensitivity test on 17 parameters deemed crucial for policy analysis. A total of 18,432 samples were generated for Sobol sensitivity analysis,[3] resulting in adjustments to the model to ensure expected behaviour and the absence of anomalies.
The complete description of the model, its purpose, entities and state variables and process overview can be found in the Supplementary Materials. In addition, the model was validated on two occasions with circular economy and mass timber experts at the Municipality of Amsterdam. The validation involved reviewing the building parameters and the information and material flows between the model's actors. During the first validation session, experts from the Municipality of Amsterdam pointed out that the real cost of mass timber buildings depends on expertise of architecture and construction companies, which can reduce the cost from the +35% included in the model to zero or cheaper than masonry buildings. This resulted in the addition of a specialisation parameter.

To ensure the heterogeneity of actors in this simplified ABS, the model consists of three kinds of owners (i.e. commercial, private, and public owners), three construction companies, a demolition company, and a material supplier. The three architecture and construction companies are capable of specialising in wood-based or masonry-based construction. Specialisation increases efficiency, reducing construction costs for the chosen material. This specialisation creates advantages and disadvantages relative to other companies. Stimuli such as specialisation programmes and subsidies influence owner preferences, further enhancing the expertise of the most efficient construction company in a particular material. However, capacity limitations prevent monopoly by one company. In the model, buildings change through demolition and construction.

[2] Material intensities show material per square metre and when multiplied by floor surface results in a material intensity estimation per building.

[3] Sobol sensitivity analysis aims to quantify how much each input parameter, alone or in combination with others, contributes to the variability of the model output (Zhang et al., 2015).

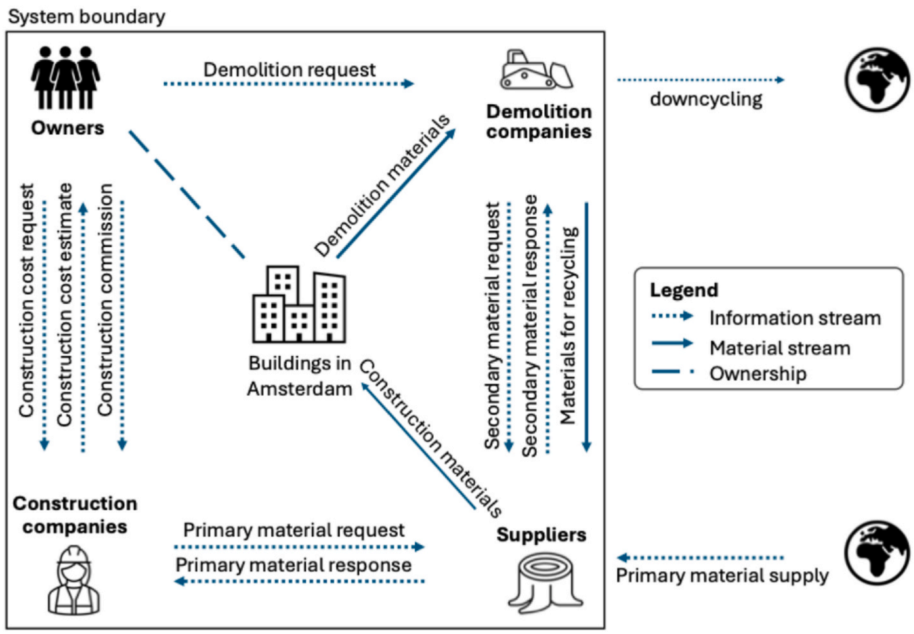

Fig. 2. Information and material flows in the model's built environment. Source: the authors.

3.3. Selected policy instruments

The ABM simulates the interaction of three policy instruments. Two policy instruments derived from the analysis of policy coherence and a proxy for a carbon tax were used to test the usefulness of ABS as ex ante policy evaluation tool. The coherence analysis of policy actions described in Section 3.1. was performed prior to the development of the model. From the coherence analysis it was observed that economic instruments were limited and less than a third were active; this was the basis for selection criteria. In addition, according to the instrument typology of Vedung (1998), economic instruments can be negative (e.g. taxes, fees) or affirmative (e.g. subsidies, grants), so it was decided to select instruments that could show the effect of both stimuli in the model. To ensure the accuracy, replicability and simplicity of the instruments in the model, only quantifiable instruments were preselected. The selected instruments are: demolition notification[4] (CircuLaw, 2023), subsidy to timber construction (Haisma, 2021), and a carbon tax proxy that increases the cost of concrete and reduces the cost of mass timber to mimic the effect of a carbon tax. The decision to use only three policy instruments resulted from the need to limit the model's output for analysis, computing power, and the exploratory nature of the study. This is considered an important limitation of the model.

4. Results

4.1. Policy coherence analysis of actions for mass timber construction

A total of 130 policy actions were identified, of which 80 correspond to instruments. Their classification under the typology of Vedung (1998) and the circular actions of Williams (2019) resulted in the following: regulatory instruments account for 62% of the 80, economic instruments to 16%, and information instruments to 22% (Fig. 3). Regarding their regime, actions are predominantly of public origin (i.e., regulatory: 59%, economic: 86%, information: 86%). The instruments of private origin were entirely contained in the documents 'Green Deal Timber Construction' (i.e. regulatory: 41%, economic: 14%, information: 14%) (Metropoolregio Amsterdam, 2021). In relation to circular city development, the resulting sample was analysed in terms of circular actions – looping (53%), ecologically regenerative (22%), adapting (25%) – and support actions –substitution (46%), optimisation (21%), localisation (22%), share (21%). There is a clear matching tendency between looping and substitution actions, as mass timber construction switches conventional construction materials (e.g., concrete, steel) by biobased materials. Yet, most policy matches in this regard do not specify the kind of mass timber construction to be considered nor specific circular strategies such as design for disassembly or modular design. Predominantly, identified actions including ecologically regenerative actions do not explicitly refer to ecologically regenerative practices as described by (Williams, 2019), for instance by integrating blue and green infrastructure or ensuring the provision of urban ecosystem services, except for the promotion and contribution to create three multifunctional forests (i.e., forest that provide timber, food, and recreation services). Regenerative actions support mass timber construction as a more ecological option compared to contemporary conventional construction materials and methods. Finally, a quarter of all actions included adaptation actions. Adaptation actions seek to adapt the built environment mainly by including mass timber construction in municipal, provincial and national environmental visions,[5] allowing experimentation, requesting the inclusion of mass timber in future development, and facilitating and investing in timber education, knowledge and expertise.

4.2. Ex ante evaluation of policy instruments for mass timber construction

The ABS conducted for ex ante evaluation of policy instruments to support mass timber construction in Amsterdam yielded several notable findings. The model simulated carbon taxation by elevating the price of

[4] A demolition notification is mandatory before a building is demolished in the Netherlands. A demolition notification allows municipalities to monitor which buildings are being demolished and how the process is being carried out. This gives them an insight into the availability of materials, particularly the amount of wood available for reuse in construction (CircuLaw, 2023).

[5] The environmental vision is instrument included in the Dutch Environmental Act that outlines the key qualities of the physical environment, the proposed development, use, management, protection and conservation of the area. It also details the key aspects of the integrated policy for the physical environment (CircuLaw, 2023).

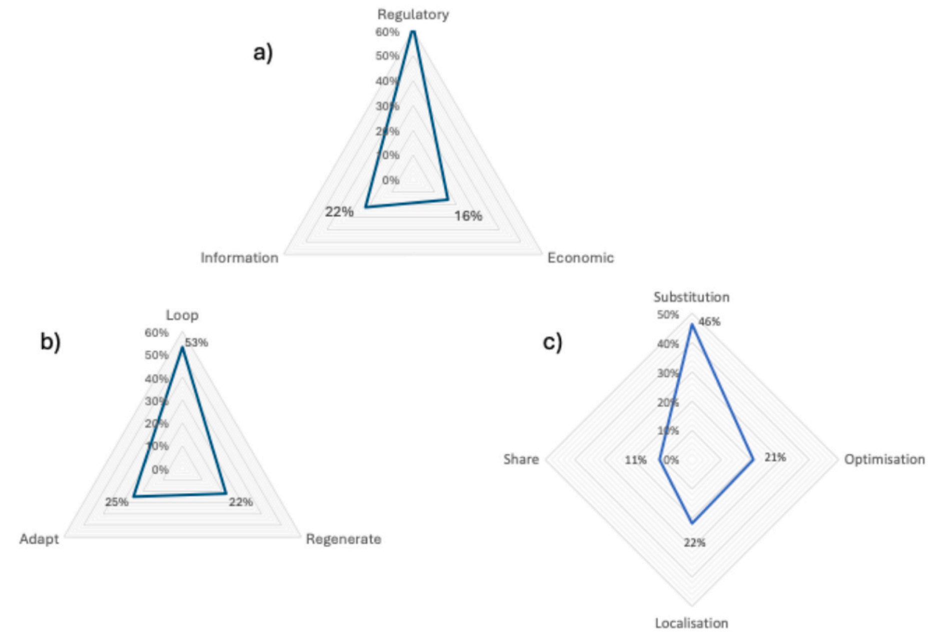

Fig. 3. Policy analysis in relation to a) type of instrument, b) circular actions, c) support actions. Source: authors.

reinforced concrete, which is predominantly used in masonry-based construction rather than wood-based construction. This price hike aimed to increase the cost of masonry-based projects in comparison to wood-based ones. While there are instances where the ratio of wood-based construction increases with concrete price increments, the correlation is not consistently significant. Even at the upper limit of concrete price increases, the rise in wood-based constructions is not guaranteed. Another policy simulation involved subsidising mass timber to lower its price. Mass timber is more commonly used in wood-based construction than in masonry-based construction. Thus, reducing the price of mass timber would also decrease the relative cost of wood-based buildings. Similar to the impact of concrete price adjustments on construction, a reduction in the model in mass timber prices can only occasionally result in increased wood-based construction on its own.

Combining instruments by implementing both a tax on reinforced concrete and a subsidy on mass timber allows for an examination of their joint effects. Upon each iteration of the ABS, an increase in the proportion of wood-based construction was observed. This shift is attributed to the relative affordability of wood-based projects compared to masonry-based ones, driven by increased demand. Consequently, architecture and construction firms are inclined to specialise in wood-based practices in the model that nonetheless in reality would require re-education and training of staff and possible the purchase of new equipment and the earlier devaluation of existing equipment to increase familiarity among owners. These dynamics contribute to lowering the costs of wood-based construction. Illustrated in Fig. 4 are 117 combinations of mass timber subsidies ($n = 13$) and concrete taxes ($n = 9$). Green dots signify combinations resulting in a wood-based building ratio higher than zero,[6] clustered in the bottom right corner where concrete costs are heavily taxed and wood costs are kept low in relation to their current cost. These results indicate the conditions that would allow an effective use of this policy blend: the difference in costs obtained by the combination of a carbon tax and a mass timber subsidy must be set to reduce the relative cost of mass timber construction beyond cost-competitive. This means a severe carbon tax rate. These otherwise obvious findings gained relevance in relation to the specialisation of

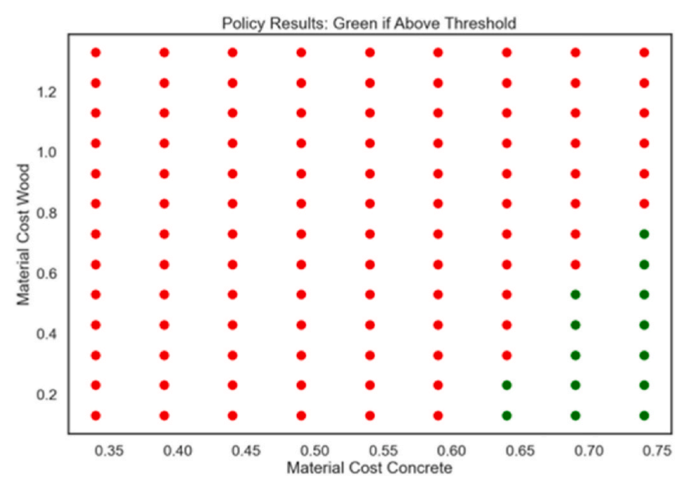

Fig. 4. Combination of the subsidy on mass timber and the tax on reinforced concrete. **Note:** Green means that the final wood-based building ratio is non-zero.

construction companies in wood-based practices, which proved to have significantly affect the construction costs of wood-based projects.

To explore the potential effects of adjusting the upfront specialisation of architecture and construction companies in the ABS, the specialisation component of all architecture and construction firms was adjusted on a scale of 1–5, where 1 represents familiarity with masonry-based construction and 5 denotes familiarity with wood-based construction. Increasing upfront specialisation in wood-based construction has a notable impact, particularly when combined with subsidies for mass timber materials and taxes on reinforced concrete, facilitating the adoption of wood-based construction methods (Fig. 5). Furthermore, specialisation rates accelerate beyond a certain threshold, influenced by various factors such as production capacity, which significantly affects the speed and volume of wood-based construction undertaken by companies.

Wood-based construction and circular practices are investigated within the model, offering insight into the interplay between circularity and the built environment. Lower values for parameters such as

[6] A wood-based building ratio higher than zero means that at least one building in the model environment is constructed using wood-based materials.

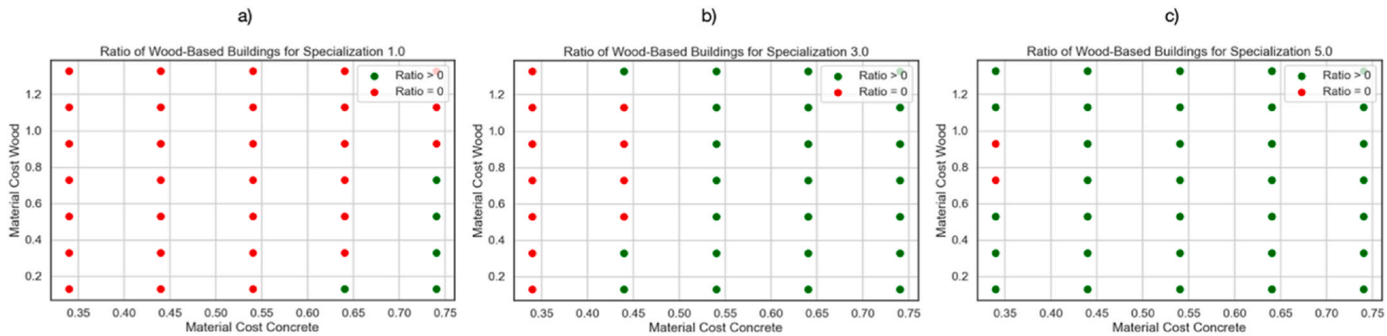

Fig. 5. Combination of a subsidy on mass timber and a taxation on reinforced concrete by Specialisation: a = 1, b = 3, c = 5. **Note:** Green means that the final wood-based building ratio is non-zero.

ratio_concrete_primary_requested and *ratio_concrete_landfilled_demolished* signify increased material recycling, reflecting greater circularity in the built environment. Findings reveal a significant correlation between factors such as concrete collection rate, recycling rate, and stock capacity with the amount of concrete landfilled and primary concrete requested. Another correlation exists between increased wood-based construction and the quantity of concrete landfilled, suggesting that any measures influencing wood-based construction would also affect concrete landfilling. Additionally, on the demand side, the selected instruments demonstrate a clear relationship with the demand for primary timber.

Finally, Fig. 6 displays two runs of the model: one without policy intervention and another with interventions. In run 1, the proportion of wood-based buildings increases over time due to varying wood recycling rates. Note that all values, except the wood-based building ratio, are aggregated, incorporating previous values. Consequently, artifacts may appear in the initial 50 model iterations due to the amplified impact of minor influences. Aggregated reporting was used due to fluctuating material demand and demolition waste. The mismatch between material released during demolition and required material highlights the need for higher recovery and recycling rates and larger material stocks, especially with increased wood-based construction. Fig. 5 indicates a rise in wooden material landfilling over time, contrasting with concrete, likely due to continued demand of concrete in wood-based construction, although the wood content in the built environment changes with the prevalence of wood-based buildings.

5. Discussion

Our findings are both expected and unexpected. Firstly, the 130 identified actions signal an increasing number of available tools to enable a transformation in the built environment of Amsterdam. It is worth noting the enabling role of the Municipality of Amsterdam in using its capacity to unveil authority instruments from existing laws and regulation in support of the city's circular economy transition through CircuLaw. In the presence of a vast set of instruments (N = 80), it was

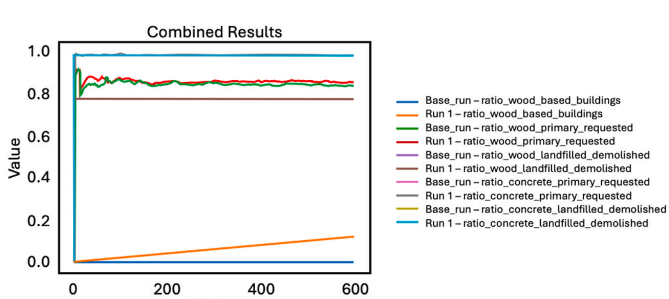

Fig. 6. Model runs with and without policy intervention.

expected to find all three types of instruments through the analysis. However, it was unexpected to find such a small number of economic instruments (16%) as in principle the circular economy seeks to transform a linear economic system into a circular one, and that only a third is active. Such a small share of economic instruments does not mean anything on its own, for a reduced number of instruments (as it is shown in this paper by a very limited test) can potentially have a considerable impact in changing practices in the construction and management of the built environment if they target the right system tweaks (Kupers, 2020). Yet, the instruments tested in this paper are not active and remain a proposal at the time of writing. These findings echo the state of the circular economy transition in the Netherlands proposed by Cramer (2022). As she explains, The Netherlands can be characterised as a country that is in a 'just before acceleration' phase, wherein (sub)national policies are in place and the involvement of local authorities is high but the circular economy still is not established (cf. Rotmans et al., 2001).

Regarding circular city development, it was expected that looping actions would prevail over ecologically regenerative and adapting ones. This has been recently observed in circular built environment research both in theory (cf. Bucci Ancapi et al., 2022b) and in a Dutch case study (cf. Bucci Ancapi, 2023). This can be explained by understanding the long-standing development of the circular economy from waste treatment principles and application that have slowly moved up the R-Ladder (i.e., moving from landfilling to incineration and recycling) (Van den Berghe et al., 2020). It was also expected to find a match between looping and low-level circular strategies such as recycling instead of more transformative strategies (e.g., refuse, reduce) that could steer a more radical transformation of the way the built environment is built, managed and constrained, for instance, by actions that prioritise the conversion of existing building stock and alternative ways to building occupation. What is more, adapting actions mostly include sectoral measures that directly did not involve the participation of citizens and communities in the re-organisation of living and building in relation to the circular economy. The stated situation regarding mass timber construction and circular city development in Amsterdam echoes the findings of the Keblowski et al. (2020) who claim that the widely-shared, transformative premise of the circular economy seems to be merely discursive to date, while following prevailing capitalistic interests and giving agency to the usual incumbents in urban decision-making. This trend was also identified in Amsterdam by Calisto Friant et al. (2023) who point out that current circular city policies fail to address social, political and ecological implications of the circular transition in the Dutch capital.

Regarding the policy instruments evaluation, it is clear that merely increasing the price of reinforced concrete or decreasing the price of mass timber does not yield consistent outcomes, largely due to the inertia within construction firms and building owners. This situation adds a new factor to the observed slow uptake of mass timber construction covered in the introduction of this article and pointed out by

Franzini et al. (2018) and Ghobadi and Sepasgozar (2023). At the model's outset, all architecture and construction companies specialise solely in masonry-based construction, resulting in a substantial premium for wood-based materials due to agents' unfamiliarity. This scenario applies to both private and public owners. Adjusting the cost of reinforced concrete alone requires a unit price far exceeding the reasonable upper bound material unit cost. However, this relationship is not universally applicable, as there are instances where combinations such as taxing reinforced concrete and subsidising mass timber prove effective, while in other cases, reducing mass timber's price fails to generate the desired impact. Arguably, and ss presented in Section 2, ex ante evaluation through a mix of policy coherence and ABS can be useful to identify underlying factors (i.e. system inertia) that may undermine the effectiveness of policy measures, given the individual behaviour and heterogeneity of agents in decision making (Walzberg et al., 2023).

There is a clear correlation between taxing reinforced concrete and the proportion of wood-based buildings, as well as subsidising mass timber and the ratio of wood-based constructions. However, this correlation lacks robustness. Combining both policies offers more promising outcomes but requires a substantial reduction in mass timber prices and an increase in reinforced concrete prices. This points brings back the discussion over the resource base of timber in the Netherlands and more generally in Europe (Peng et al., 2023; World Resource Institute, 2023), also covered in the introduction, for the price of mass timber will depend on its availability in a European context marked by recent policy developments around the "Fit for 55" policy package. The latter does not include mass timber construction as a primary strategy nor provides certainties about the balance between mass timber availability, forestry expansion, and forest conservation and restoration (cf. EC, 2021).

Next to the cost discussion, it is important to highlight the unexpected finding regarding the unavoidable need of concrete in mass timber construction. While the potential of biobased construction has been assessed and found favourable in reducing CO2-eq emissions (Buchanan and Levine, 1999; Churkina et al., 2020; Himes and Busby, 2020), little attention has been given to the use of concrete in buildings foundations depending on building types, height, and function. The discussion on policy choices for building materials is often framed in terms of either mass timber or concrete or other non-biobased materials (UNEP, 2023). However, this research emphasises that mass timber construction still needs other non-biobased materials such as concrete. This ABS shows a large material intensity and amount of concrete being released after demolition, which can be re-integrated in the built environment if properly estimated and recycled. It is worth noting that urban mining research has been conducted in Amsterdam for types of metals, as a critical resource, in its built environment (AMS Institute, 2016; Koutamanis et al., 2018), yet a massively and locally available resource such as concrete to be reused or recycled is not included in the policy documents analysed for this study. Policy incentives for mass timber construction in Amsterdam should consider when to incentivise locally available reused or recycled concrete, considering its spatial impacts (cf. Van den Berghe and Verhagen, 2021). This unexpected finding backs the usefulness of ABS in CE policy evaluation stated by Walzberg et al. (2023) (Section 2), when referring to the identification of decisions that yield increased circularity and the accounting of externalities associated with CE activities (i.e. including available secondary resources in CE policy).

A more effective policy approach to promoting mass timber construction in Amsterdam is to increase the familiarity of architects and builders with these materials. Knowledge sharing, as outlined in the 'Green Deal Timber Construction', can improve the effectiveness of policy instruments. Companies' familiarity influences construction costs and the premium paid for mass timber structures, but some avoid them due to concerns about cost-effectiveness, particularly for projects that favour masonry. Specialisation drives divergence, with masonry remaining vital for certain types of construction. Dissemination of knowledge across firms and supply chains can narrow the knowledge gap, reducing costs and enabling transformative policy outcomes. Ex ante policy evaluation may support the identification of effective systemic adjustments within existing policy frameworks (Bemelmans-Videc, 2003), offering greater effectiveness than creating entirely new policies (Colander and Kupers, 2014; Kupers, 2020). Policy formulation can also be enhanced through ex ante policy evaluation. As discussed in Section 2, policy formulation as a more technical and 'backroom function' is the stage of the policy cycle where instruments are chosen and fine-tuned to achieve a particular objective (Fischer et al., 2007). This article argues that knowledge sharing is as crucial as selecting the right economic instruments to trigger a chance in construction practices Amsterdam.

The analysis and ABS, however, faced several limitations and can be improved in certain directions. Firstly, the analysis included only local, regional, and national policies. Undoubtedly, the inclusion of European-level policies can yield more comprehensive insights regarding policy instruments for the adoption of mass timber construction. Secondly, data regarding material intensities of timber could be improved by building up a repository based on the Dutch context. Thirdly, an important model limitation is the lack of data on concrete and timber released during building adaptation and renovation processes as well as about the quality of the released materials, which could be obtained by estimating an average material intensity. Fourthly, the model could also be improved by adding a Geographical Information System (GIS)-based visual representation of the built environment, as well as an estimation of CO2-eq emissions resulting from material transport throughout Amsterdam. Finally, our findings resulted from using only three policy instruments, of which only one (i.e. demolition notification) is in place in Amsterdam. This decision followed the desire to test economic instruments as the circular economy aims to change the current economic system, however, the results of our model remain speculative.

In addition, it is worth discussing the analytical concepts used in this article, namely policy actions, instruments, coherence and ex ante evaluation. This is one of the first articles to focus on policy actions as an umbrella term for more or less defined instruments. This decision was made to include a wider range of policy options in an early sustainability transition, but most policy actions that have not been implemented through a concrete policy instrument remain open for scrutiny and lip service in the meantime. Various typologies of policy instruments exist, but this article has drawn on that of Vedung (1998), which is notable for its simplicity and clarity. It may be argued that this typology does not capture all the mechanisms through which governments effect change; this is true. It might be interesting to explore other typologies, such as that of Hood and Margetts (2007), which also includes a typology (i.e. organisation) that reflects government capacity and the own resources it can use to effect change, for example by simplifying approval procedures or providing physical space. Finally, the use of policy coherence and ex ante evaluation was intended to suggest a way of analysing circular city policies during policy formulation or early stages of implementation. They can by no means be used to assess the overall effectiveness of policy decisions; the use of ex post evaluation remains necessary to assess policy effectiveness. These improvements could further validate the proposed ex ante analysis and ABS as tool for policymakers in circular city policy formulation.

This research has important theoretical and social implications. Theoretically, this research advances i) the study of coherence in circular city policies and ii) the exploration of ABS to evaluate CE policies in the construction sector, addressing gaps identified as a major obstacle for cities in their transition towards circularity (OECD, 2020) and as minimally explored in research (Rizzati and Landoni, 2024), respectively. From a social and managerial perspective, it underlines the importance of knowledge dissemination and capacity building within the construction sector, especially among design and construction firms, positioning them as essential components of effective policy mixes. In addition, it derives policy implications such as the need for i) well-aligned policy combinations (e.g. subsidies and carbon taxes on concrete) to drive systemic change, ii) the integration of secondary resources such as recycled concrete to reduce reliance on primary materials, and iii) dynamic policy design that allows policymakers to refine strategies through ex ante evaluation prior to implementation.

6. Conclusion

The aim of this article was to evaluate policy actions for mass timber construction by means of ex ante policy evaluation. The case of Amsterdam was selected given recent policy developments regarding circular economy and mass timber construction, making it a particular case. This article found a total of 130 policy actions and 80 policy instruments amongst those actions. Next to this, a prevailing focus on looping and substituting actions over ecologically regenerative and adapting ones was also identified, echoing previous findings that characterize circular built environment policies as building upon long-standing waste management principles aiming to shift from landfilling to incineration and recycling. The model and resulting simulation highlight the potential transformative power of economic instruments paired with improvements in capacities around mass timber construction practices, as well as the unavoidable role of (recycled) concrete in supporting a more circular and biobased built environment in Amsterdam. In conclusion, this article supports the usefulness of ex ante policy analysis as tool for policymaking regarding the transition to a more circular built environment in Amsterdam and possibly elsewhere. This research direction can benefit from (i) expanding ex ante policy analysis to supranational policies, (ii) the gathering and structuring of data in relation to material intensities of building renovation and adaptation, (iii) integrating Geographic Information Systems to the model for the estimation of carbon emissions in material transport, (iv) further improving the visualization of simulation to better inform policymaking processes and future policy cycles, and (v) combining this analysis with an study of the politics and polity around (mass timber) construction to explain how policy actions for mass timber construction are decided and designed. This article concludes by recommending that (sub)national policy makers consider ex ante evaluation when dealing with complex policy issues where there is insufficient information on their effectiveness and coherence. Furthermore, policy makers are encouraged to evaluate the impact of a policy by its instruments rather than by its ambitions, as instruments are the concrete actions to change structural governance issues in the development of circular cities.

CRediT authorship contribution statement

Felipe Bucci Ancapi: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marvin Kleijweg:** Visualization, Validation, Software, Formal analysis, Data curation. **Karel Van den Berghe:** Writing – review & editing, Supervision. **Neil Yorke-Smith:** Writing – review & editing, Supervision. **Ellen van Bueren:** Writing – review & editing, Supervision.

Data availability

The dataset containing the 130 policy actions for mass timber construction in Amsterdam and their analysis is available at the open access 4TU.ResearchData repository. Data on the distribution of building in Amsterdam by type and ownership, as well as the data on the floor surface of residential and utility buildings were extracted from Statistics Netherlands (2023a), the open access database of the Dutch Statistics Bureau. Recycling rates for the Dutch built environment were obtained from (Zhang et al., 2020). Parameters to determine a building's lifespan through a Weibull distribution were sourced from Deetman et al. (2020) and Yang et al. (2022). Data for the calculation of material intensities for concrete and wood were obtained from Sprecher et al. (2022) and Smith and Wallwork Engineers (2023), respectively. The latter data was acquired with the help of Wallwork Engineers, an engineering company specialized in wood-based constructions. The material intensities for wood-based buildings are derived from their project dataset. The dataset is privately-owned and therefore it is not publicly available.

Code availability

The code of the model is available at the 4TU.ResearchData repository through this link,[7] the data is maintained by the corresponding author.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT and DeepL only in order to improve the conciseness and readability of the article. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.124516.

Data availability

Data will be made available on request.

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