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Article:

1 **Conceptualizing systems thinking and complexity modelling for circular**

2 **economy quantification: A systematic review and critical analysis**

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10 **Abstract**

11 Quantification of circular economy is essential for effective implementation, yet also

12 fundamentally challenging, because it is inherently complex, featuring multiple interactions

13 and system-level dynamicity. Two main approaches of systems thinking, commonly used to

14 model complexities in intricate systems, are: System Dynamics (SD), providing a top-down,

15 macroscopic view; and Agent-Based Modeling and Simulation (ABMS), offering a bottom-

16 up, microscopic perspective. Here we conducted a PRISMA-ScR review, examining 60

17 studies applying SD or ABMS to circular economy, across sectors such as bio-based

18 materials, construction, and industrial symbiosis. Both methods capture aspects of

19 circularity's feedback loops and time evolution, but they are often used in isolation in the

20 absence of integrated platforms along with concerns over computational costs. This limits

21 their capacity to comprehensively model internal dynamics at multiple scales and provide

22 system-wide decision support. Few studies explore the potential of combining SD and ABMS

23 or attempt to integrate them with static tools, such as life-cycle assessment and multi-criteria

24 decision analysis. Standardised metrics and operational holistic evaluation tools incorporating

25 economic, environmental, technical and social sustainability aspects are missing – especially

26 with the latter. A more unified and comprehensive systems approach to support informed

27 decisions on circularity would improve evidence-based policymaking and empower wider

28 industrial adoption.

29

32

1   Introduction

The concept and practice of circular economy (CE)/circularity intend to go beyond the established practices of waste management and resource recovery, towards an even more sustainable management of material resources. Numerous circular economy/circularity definitions have been proposed, as summarised in detail by Kircherr and co-workers (Kirchherr et al., 2023, 2017). For example, the United Nations Environment Programme (UNEP) described CE as *"an economy that reduces consumption of resources and the generation of waste, and reuses and recycles waste throughout the production, distribution and consumption processes"* (United Nations Environment Programme (UNEP), 2011). More recently, BS ISO 59004:2024 defined circular economy as an *"economic system that uses a systemic approach to main a circular flow of resources by recovering, retaining or adding to their value, while contributing to sustainable development"* (The British Standards Institution, 2024a). An alternative earlier definition, closer to the beginning of the recent update of the circular economy notion, proposed that *"[... circular economy] is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles"* (Ellen MacArthur Foundation, 2013)*; therefore,* encouraging a shift from 'cradle-to-grave' thinking to a 'cradle-to-cradle' philosophy, thus promoting the idea of maximising the positive 'value' associated with material, components and products (MCPs). This wording emphasises the concept of MCPs' value regeneration and redistribution through their entire lifecycle, and multiple iterations thereof.

Nonetheless, this approach does not define (specify) the inherently multi-dimensional and therefore complex meaning of *'value'*, which usually goes beyond the monetary loss/benefits, to incorporate environmental benefits, social equity and prosperity, and minimal technical performance loss (e.g., design for reuse) (Iacovidou et al., 2017b, 2017a; Millward-Hopkins et al., 2018). BS ISO 59004:2024 defined 'value' as *"gain(s) or benefit(s) from satisfying needs and expectations, in relation to the use and conservation of resources"* (The British Standards Institution, 2024a). Such a value transforms: it is created/destroyed/transferred between places and owned by organisations, as MCPs are physically moved and transformed in the extraction of resources, materials, components, semi-finished goods and goods are manufactured, retailed, used and becoming after-use/waste and entering the waste and resource recovery/disposal part of the cycle. Measuring this value as an attempt to quantify circularity is therefore feasible only in a comparative way,

66 within a system at which the value carried by MCPs takes specific 'states'/'levels' at different

67 points.

68   For example, simplified typologies on the mode of circularity have been historically

69 narrated via 'R'-type based frameworks (**Table 1**), and the definitions of the various R's are

70 provided in **Supplementary Material S.2** as per BS ISO 59004:2024 (The British Standards

71 Institution, 2024a). They offer a simple conceptual hierarchy of circularity modalities

72 applicable at various MCPs lifecycle stages, focusing on slowing, closing, or narrowing

73 resource flows. Similarly, quantifying the nature and degree of circularity achieved by these

74 R-type modalities, requires as a bare minimum definition of ratios between parts of a material

75 flows system. From a whole system's perspective, the implementation of each 'R' philosophy

76 is highly time-dependent, short- and long-term impacts (i.e., time dynamicity and delays)

77 with potential benefits (e.g., diversion from landfill) or drawbacks (e.g., insufficient recycling

78 capabilities driving increased disposal), and it depends on stakeholders' activities along value

79 chains and value networks (Walzberg et al., 2022b), i.e. in material flow systems.

80 **Table 1.** A variety of 'R' concept-based frameworks proposed.

Framework	'R'- type content	Reference
3-Rs-based	Reduce, Reuse, and Recycle	Brennan et al. (2015)
4-Rs-based	Reduce, Reuse, Recycle, Recover	Yang et al. (2017)
6-Rs-based	Reduce, Redesign, Recover, Reuse, Remanufacture, Recycle	Jawahir and Bradley (2016)
9-Rs-based	Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover energy	Van Buren et al. (2016)
10-Rs-based	Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover and Refuse	Kirchherr et al. (2017)

81

82   In such material flow systems, multiple variables may cause system dynamicity: i.e.,

83 qualitative and quantitative, endogenous and exogenous, linear or non-linear. Understanding

84 stocks and flows of material, energy, finance, etc. is key to sufficiently describe such a CE

85 system, where multiple stakeholders are involved along the entire value-chain, sometimes in

86 closed loops introducing feedback in the system, each aiming to maximise its own benefits,

87 therefore transforming the monetised or wider perceived 'value' of MCPs at each system

88 point over time. As a result, such systems feature numerous complexities, and feature trade-

89 offs among aspects of 'value' which would be very difficult, if at all possible, to

90 capture/summarise solely through traditional analytical, equations-based, approaches (Sun et

91 al., 2016).

92   Similarly, system boundaries (time, geographical, administrative, scale) may play a

93 crucial role in systems thinking, and while the actions of system agents may not reveal

94 impacts at a *'micro'* scale, they may do so at *'meso'* or *'macro'* scales. For example, even

95 where systems tend towards a balanced state, external agents all along the value chain, such

96 as early adopters of new technologies, can disrupt this state until a new balanced state

97 develops. A series of system-level failures have been proposed as preventing the creation and

98 operation of genuine circular economy (Velis, 2018): description, verification and

99 quantification of such phenomena, however, would necessitate a systems approach.

100 Quantifiable metrics of circularity could be exhibiting highly non-linear behaviours, as a

101 system emerges through the adaptive nature of agents. However, the BS ISO 59004:2024

102 does not specifically mention or define *'micro'*, *'meso'* and *'macro'* level implementation of

103 CE, and their associated modelling of complexity (The British Standards Institution, 2024a).

104   Therefore, even though BS ISO 59020:2024 provides an indicative list of circularity

105 indicators, we argue that ultimately, effective qualification and quantification of circularity

106 by default can be only achieved through a so-called 'systems thinking' approach.

107 Additionally, BS ISO 59020:2024 mentions that value in CE systems is *"complex, and*

108 *difficult to measure, and requires careful consideration"*. But it does not provide or propose a

109 structured process to model 'value' (The British Standards Institution, 2024b). Simply put,

110 systems thinking adopts holistic and interconnected approaches to understanding and

111 addressing inherent complexities of an entire system, rather than its isolated components

112 (Arnold and Wade, 2015; Bassi et al., 2021; Demartini et al., 2023). Richmond (1994)

113 defined systems thinking as the art and science of making trustworthy decisions about

114 behaviour by developing deep understanding of underlying structures. Meanwhile, Sterman

115 (2000) defined systems thinking as an approach and mindset for understanding and analysing

116 complex systems as interconnected and dynamic entities, and thus asserting the principle of

117 dynamic complexity for solving systemic challenges. It involves recognizing that a system is

118 more than the sum of its parts; and that its behaviours and properties emerge from

119 interactions and interdependencies among its components. A methodologically analytical

120 approach has therefore the potential to identify leverage points in the system under a

121 multiplicity of conditionalities.

122   Systems thinking and its pertinence to CE are discussed in detail **S.3.1** and **S.4** of the

123 **Supplementary Material** (denoted as **S** for tables, figures, and sections). Two prominent

124 approaches in this regard are system dynamics modelling and agent-based modelling and

125 simulation (ABMS). System dynamics and ABMS approaches can, to varying degrees,

126 address challenges around static and linear descriptions of circularity. While **Sections S.3.2**

127 **and S.3.3** offer more details of system dynamics and ABMS theorising, the approaches are

128 summarised below. System dynamics models enable us to analyse the dynamic non-linear

129 relationships and time-dependent pattern changes of complex systems. It considers the

130 complexity of systems thinking by employing feedback loops, stocks and flows diagrams,

131 time delays, nonlinear relationships, and causal loop diagrams, while adopting an iterative

132 approach. Whereas ABMS is a computational technique used to simulate complex systems

133 composed of autonomous entities called agents. Each agent has its own behaviour, decision-

134 making rules, and interactions with other agents and the environment. This approach has been

135 widely adopted for its ability to model complex human-environmental systems by capturing

136 the dynamics and heterogeneity of individual actors.

137   To date, applied research on CE and systems thinking has often focused on complexity

138 modelling of the *'micro'* scale. For example, addressing the meaning of systems thinking in a

139 CE context, but not the inherent complexities and dynamicity of the whole system in *'macro'*

140 scale (Iacovidou et al., 2021). Recent research has advanced CE, but often still omitting

141 systems thinking and even more so its corresponding quantification (**Table 2**), which, as we

142 argue, could provide a sound base for more holistic, meaningful, and reliable circularity

143 analytics.

144 **Table 2.** Reviews on systems thinking and its quantification from a CE perspective.

Summary	Scope limitations	Reference
Focused on common modelling approaches to analyse industrial symbiosis.	Did not focus on dynamics of circularity metrics and parameter quantification.	Demartini et al. (2022)
Reviewed life cycle assessment studies of a biorefinery system.	Omitted quantification of systems thinking by complexity modelling.	Vance et al. (2022)
Integrated review of CE concerning construction and the built environment.	Omitted systems thinking and dynamic quantification of CE.	Çimen (2021)
Comprehensive review on adoption of system dynamics and agent-based models in construction waste management.	Did not focus on the necessity of systems thinking, its complexity, and thereafter dynamic quantification of circularity metrics.	Ding et al. (2018)

145

146   To the best of our knowledge, there are no reviews and analyses with a

147 comprehensive scope on the quantification of circularity through systems thinking and its

148 associated complexity modelling. Therefore, here we adopt a systematic scoping review

149 approach according to PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and

150 Meta-Analyses for Scoping Reviews) (Peters et al., 2020; Tricco et al., 2018), concerning the

151 application of systems thinking through system dynamics and ABMS (refer to **Sections S.5 -**

152 **S.8** for more details). Our approach and scope can offer novel insights on:

153   a) considering how complexity arises in CE systems, highlights the relevance of systems
154   thinking applied to CE, and particularly its quantification;

155   b) by the way of case studies categorised by sector, it applies a magnifying lens on
156   applications of system dynamics and/or agent-based modelling in quantifying
157   different aspects of CE in the bio-based, construction, electrical and electronics
158   products, single materials, manufacturing, industrial symbiosis, and miscellaneous
159   sectors, specifically also considering circularity metrics and wider parameters, which
160   BS ISO 59004:2024 and BS ISO 59020:2024 do not provide; and,

161   c) by describing and analysing how other decision-support tools have been integrated
162   with system dynamics and ABMS aiming at more refined analytics.

163   Additionally, we also consider case study geography, along with the impact of policy

164 and governance aspects, where available. Notably, we do not analyse, criticise or

165 comparatively examine the specific findings of each publication we have reviewed here, but

166 we instead focus on documenting and examining their methodological approaches to

167 quantifying circularity via systems methods.

168

169 **2   Methodological Approach to Systematic Literature Review**

170 We conducted a systematic scoping review following the PRISMA-ScR guidelines (Peters et

171 al., 2020) and the associated preferred reporting items checklist (Tricco et al., 2018) (Refer

172 **Figure 1.a – 1.b** and **Table S.3**). The review explored three specific questions:

173   • RQ1: What were the contexts/necessities of applying system dynamics modelling and
174   ABMS approaches in CE?

175   • RQ2: Which types of decisions were provided through system dynamics and ABMS
176   approaches?

- RQ3: Were any other tools/methods applied in conjunction with system dynamics, and ABMS? If so, why?

The complete flow diagram of the work is presented in **Figure 2**. The search was practically restricted to recently published articles, arbitrarily defined as in the last 9 years at the point of the start of the review: 2016-2024. However, this approach was justified by looking at earlier outputs, where only 3 relevant articles were retrieved
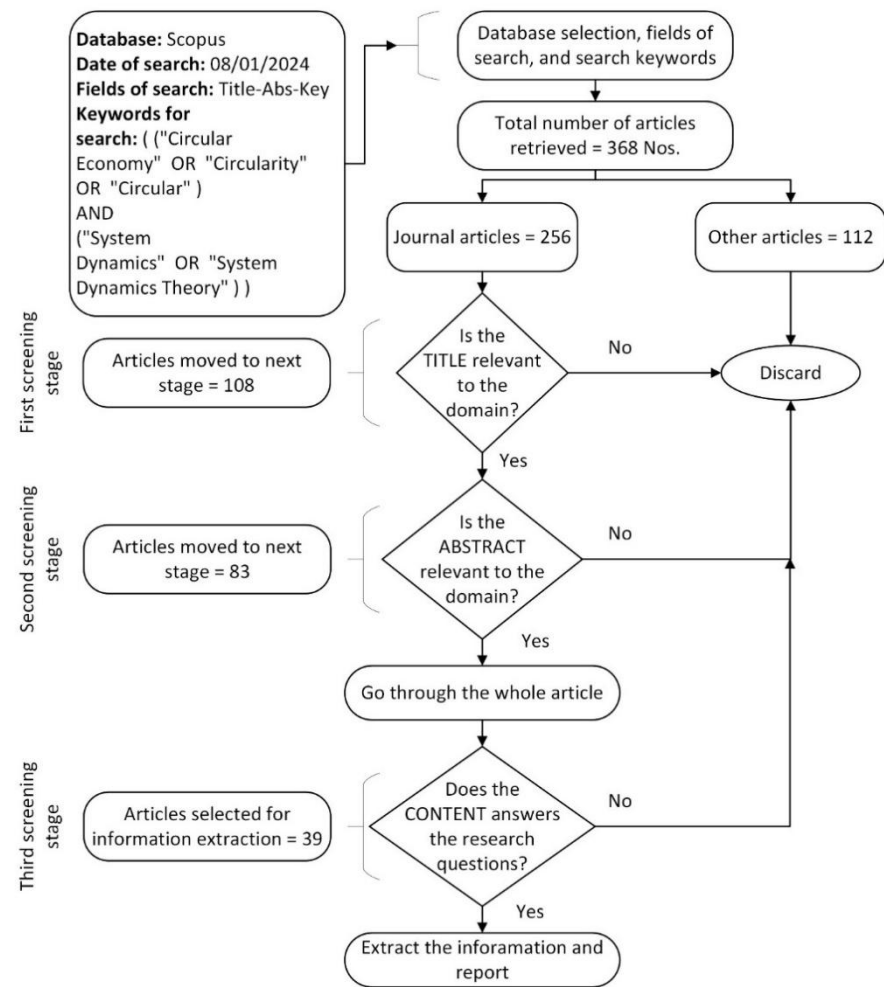
Figure 1.a. Literature selection flow diagram to identify key publications related to applications of system dynamics in circular economy context.
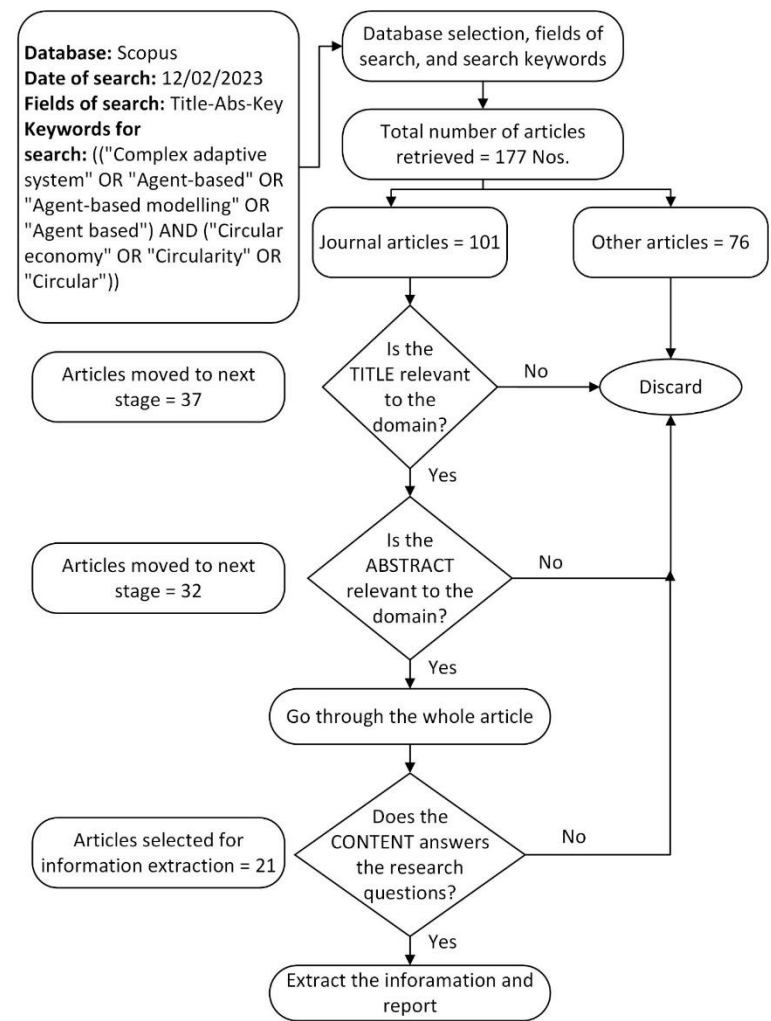
Figure 1.b. Literature selection flow diagram to identify key publications related to applications of agent-based modelling and simulation in circular economy context.

184   from 2003-2015, and these were not useful to answer the research questions. Having

185   identified the articles which answered the research questions, these were grouped

186   according to application domain. This identified the following sectors: bio-based,

187   construction, electrical and electronic products, single materials, manufacturing, industrial

188   symbiosis and miscellaneous. The precise definitions of these sectors are given in the

189   relevant **Sections**.

190

191   **Figure 2.** General methodological flow diagram and signposting of information for this research.

192

3 Sector-wise Applications of SD and ABMS in Quantitative Circular Economy

3.1 Bio-based Sector

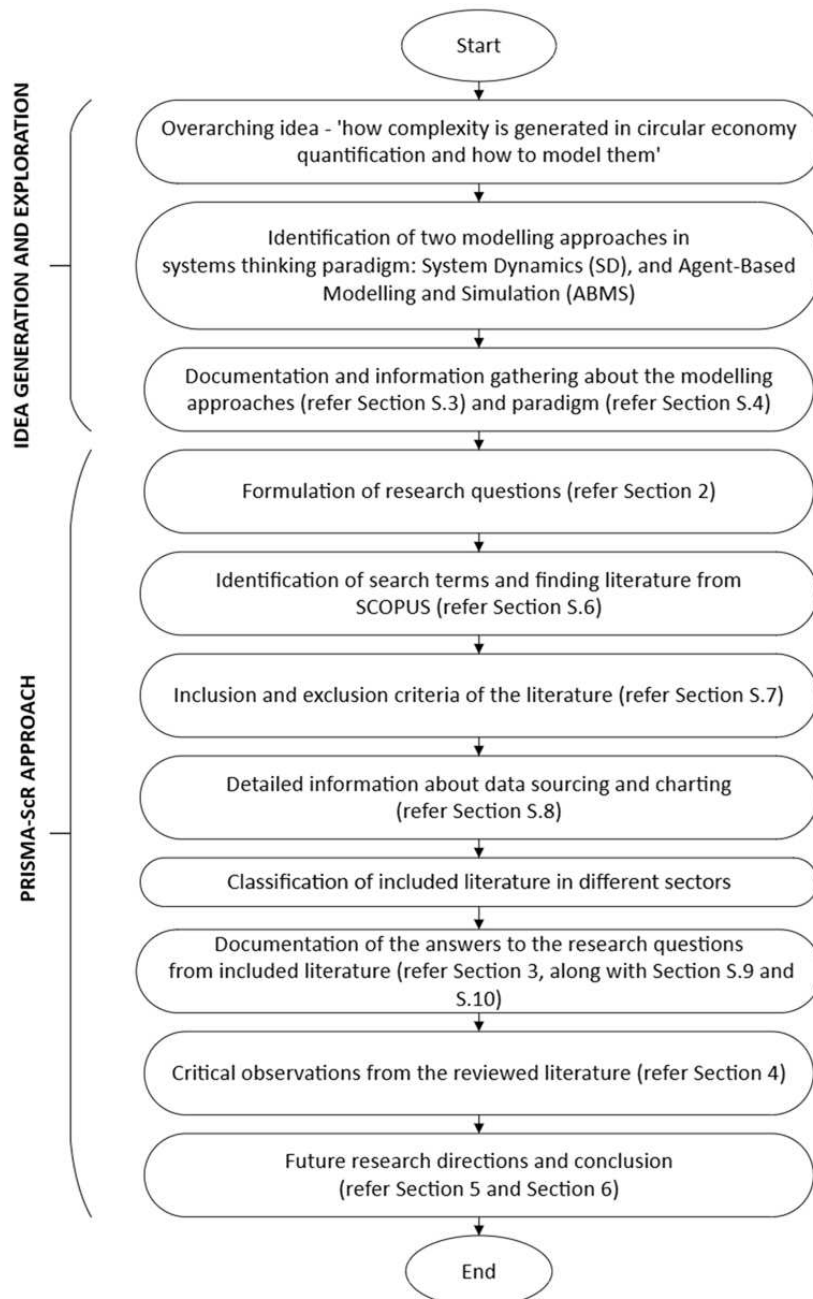We have used the term bio-based sector to refer generally to material of organic or biological origin. Exact application domains are given in **Table 3** and **Table 4**.

3.1.1 System dynamics modelling in bio-based sector

Articles cover a diverse range of contexts, such as; food waste reduction in the food, energy, water, and climate (FEWC) nexus (Parsa et al., 2024, 2023) or through an online food sharing application (Ranjbari et al., 2024), the flow of chicken and associated waste products in the economy (Abbasi et al., 2024), addressing reactive nitrogen's societal contribution (Xing et al., 2023), utilising waste cooking oil as second-generation fuel (de Carvalho Freitas et al., 2022), examining urban sustainability transition in food, energy, water, and waste (FEWW) sectors (Valencia et al., 2022), and scrutinising phosphorus recycling process (El Wali et al., 2021).

The initial step of system dynamics modelling involves the creation of causal loop diagrams, offering a qualitative understanding of intricate relationships between different parts. Afterwards, stocks and flows within the system are identified, and quantitative analysis is executed by stocks and flows diagrams. Some authors exclusively presented the causal loop diagrams before developing the stocks and flows diagrams (Abbasi et al., 2024; de Carvalho Freitas et al., 2022; Ranjbari et al., 2024; Xing et al., 2023), whereas some incorporated the causality of different variables within the stocks and flows diagram (Valencia et al., 2022). Some did not report the stocks and flows diagram directly, but presented the flows of materials, energy, or finance through Sankey diagrams (Parsa et al., 2024, 2023).

Stocks and flows diagrams were used to illustrate the dynamic interactions of flows of FEWC between different sectors in an agri-food supply chain (Parsa et al., 2023), to highlight socio-economic interactions coupled with material and finance flows (Parsa et al., 2024), and to integrate the forward and reverse value-chain mapping in chicken farming (Abbasi et al., 2024). Furthermore, they aided the understanding and mapping of flows within various scenarios: for example reactive nitrogen flows from food waste and its associated impact on the nitrogen cycle (Xing et al., 2023); waste cooking oil generation pattern by households, and its impact on water pollution (de Carvalho Freitas et al., 2022); food, energy, water and waste flow (Valencia et al., 2022). Some authors even modelled material flows (viz., surplus

food) with the knowledge of the system entities (viz., population) (Ranjbari et al., 2024) and coupled materials flow with social metrics (El Wali et al., 2021).

System dynamics model is in principle able to identify key leverage points of systems, and in scenario generation and metrics forecasting, which, in turn, could help policy recommendations. Key leverage points may not be obvious in baseline scenarios but emerge through examining various alternative scenarios. For instance, crop planting and aquaculture were identified through scenario generation as the main sectors for emitting reactive nitrogen (Xing et al., 2023). In de Carvalho Freitas et al. (2022), household cooking oil consumption patterns were identified as the key influence on water pollution. Meanwhile, food waste and environmental footprints could be minimised by reducing waste generation at consumer and redistribution levels (Parsa et al., 2023). Children's knowledge of a food-sharing app was identified as a key lever to reducing food waste (Ranjbari et al., 2024). In Parsa et al. (2024) the key sectors for food waste minimisation were identified which, in turn, benefitted the socio-economic metrics. Some studies demonstrated self-sustainability through landfill gas and stormwater reuse (Valencia et al., 2022). Holistic linkages between small and medium-scale farms have been emphasised for sustainable development (Abbasi et al., 2024). Additionally, the practice of CE enhanced global phosphorus security and social prosperity in low and middle-income countries as found in El Wali et al. (2021).

Additionally, all these studies mapped stocks and flows over extended time periods, across various geographical scales (El Wali et al., 2021) and coupled them with various CE metrics (see **Table 3**), not only to map the current situation, but also to forecast future scenarios. The variables considered in the models were often non-linear. For details refer to **Table S6-S7**.

Table 3. Case-study domains, quantified metrics, consideration of 'R' principles, and use of other tools in system dynamics applications within the bio-based sector.

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	Reference
Chicken farming	Behaviour of egg laying chickens, egg, hatchery, and day-old chick stocks, poultry litter and poultry litter to banana farm stock, chicken flow to slaughterhouse, waste flow to fish farm, total	Reuse, repurpose, recycle, recover	n.a.	Abbasi et al. (2024)

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	Reference
	income, profit, and total cost of the stakeholders			
Food-waste mitigation strategy by food-sharing platform	Total amount of food waste prevented, total CO_2 emissions prevented, and food-sharing platform performance.	Rethink, reduce, and reuse	Bass diffusion model to account the adoption of food-sharing app by the population.	Ranjbari et al. (2024)
Food waste reduction	Intermediate cost, total GVA, and sectoral GVA, severe food insecurity rate, food waste generation, redistribution cost, redistribution benefit	Reduce, reuse, recycle, recover	n.a.	Parsa et al. (2024)
Food waste reduction in food, energy, water, and climate (FEWC) nexus	Food footprint, food waste generation, energy footprint, water footprint, and carbon footprint.	Reduce, reuse, recycle, recover	Group model building to create, refine, and restructure the system dynamics model with stakeholders' interventions.	Parsa et al. (2023)
Food and agricultural system	Total reactive nitrogen output, air nitrogen emission, soil reactive nitrogen emission, water reactive nitrogen emission	Reuse and recycle	n.a.	Xing et al. (2023)
Fuel: waste cooking oil to second generation fuel	Household consumption and industrial consumption of vegetable oil, waste oil not recycled, water pollution, and oil to recycle	Recycle	n.a.	de Carvalho Freitas et al. (2022)
Food, energy, water, waste nexus	Reclaimed water utilization, food wate reuse, waste to energy generation, food production, carbon footprint, water footprint, water resilience index, food supply index and different types of wastes produced.	Reduce, recycle, reuse, recovery	TOPSIS (Technique for order of preference by similarity to ideal solution), a MCDM tool was used to identify the most suitable scenario based on sustainability and resilience indicators.	Valencia et al. (2022)
Phosphorus (P) recycling	Worker safety, employment equality, employment rate, poverty rate, child labour, water use, nutrition supply, P efficiency and security	Recycle and recovery	n.a.	El Wali et al. (2021)

251   n.a.: not applicable

252

3.1.2 Agent-based modelling and simulation in bio-based sectors

ABMS is a bottom-up system modelling approach. In Farahbakhsh et al. (2023) it was utilised to identify the barriers to adopting emerging technologies in waste treatment plants, exploring potential contribution of chemical recycling of carbon-containing waste of municipal solid waste (MSW). It has also been used for dynamic life-cycle sustainability assessment to contribute to UN sustainable development goals (UN SDGs) (Voss et al., 2022), and to investigate households' intentions regarding recycling (Tong et al., 2018).

In general, we sense that ABMS is preferred over systems dynamics when the heterogeneities of the stochastic agents are essential to modelling. In Farahbakhsh et al. (2023) it was induced by agents' (viz., waste treatment plants) environmental awareness, investment required to adopt emerging technologies, and expected returns, etc. In Voss et al. (2022) agents were characterised based on their geographic locations, annual residual MSW (rMSW) production volume, treatment capacity, etc. In Tong et al. (2018), households' intentions towards recycling and/or landfilling were considered as heterogeneities.

These heterogeneous agents sustain by dynamically adapting to their environment. For example, in the case of valorising organic waste into high-end products, the agents adapted within a global market in response to economic, social and environmental pressures (Farahbakhsh et al., 2023). Strict sustainability regulations led agents (viz., administrative areas, and waste treatment plants) to adapt in Voss et al. (2022) regarding circular utilisation of organic residual MSW as a chemical feedstock via gasification. While in Tong et al. (2018) waste separation and recycling were agents triggered by changes in consumer behaviour.

Interactions between agents and with the environment can lead to the emergence of new, not easily foreseeable, behaviours. This can result from social pressure provided by other agents to adopt CE technologies (Farahbakhsh et al., 2023), or be reward-driven (Tong et al., 2018). Temporal (Farahbakhsh et al., 2023; Tong et al., 2018; Voss et al., 2022) and spatial considerations (Tong et al., 2018; Voss et al., 2022) offer a nuanced understanding of dynamic processes. This consideration over temporal scales led to scenarios analysis and metrics quantification as outlined in **Table 4** (for further details see **Table S20-S22**).

Table 4. Case-study domains, quantified metrics, consideration of 'R' principles, and use of other tools in agent-based modelling applications within the bio-based sector.

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	Reference
European organic waste treatment facilities	Volatile fatty acid platform (VFAP) adoption rate by changing the: (a) subsidies (both investment and operational), (b) market growth in polyhydroxyalkanoates (PHA) segment, (c) improvement in technological efficiencies, (d) social pressure.	Recycle	n.a.	Farahbakhsh et al. (2023)
Carbon containing waste of MSW	Climate change, terrestrial acidification, fossil resource scarcity, system cost, and impact on local environment for different defined scenarios.	Recycle	n.a.	Voss et al. (2022)
Household recyclable wastes	Participation rate of households regarding three choices: landfilling, placing waste at a central container, or being collected, every day for a period.	Recycle, recovery	Theory of planned behaviour (TPB) was used to identify key influencing factors affecting the residents' inclination to recycling.	Tong et al. (2018)

n.a.: not applicable

3.2 Construction Sector

The construction sector refers to anything related to construction, and a detailed consideration of the domains covered is presented in **Table 5**. No studies were identified that use ABMS to quantify circularity.

3.2.1 System dynamics modelling in the construction sector

System dynamics has been used for a range of applications in the construction sector. It was used to examine the circularity potential of recycled paver blocks (RPB) (Gandhi et al., 2024), and the decarbonisation potential of US commercial buildings (Eissa and El-adaway, 2024). Ghufran et al. (2022) explored enablers for the CE transition in the construction sector, focusing on causal interdependencies, while Kliem et al. (2021) specifically concentrated on policy. Mostert et al. (2022) meanwhile estimated and forecast construction and demolition materials flows in the German construction sector.

Causal loop diagrams have been constructed to depict the dynamic interdependencies between cost components when manufacturing recycled paver blocks (Gandhi et al., 2024), to examine causal links between CE enablers in the construction industry (Ghufran et al., 2022),

and public policy instruments' impacts on CE business model (Kliem et al., 2021). Stocks and flows diagrams meanwhile aided quantification of the temporal evolution of manufacturing cost of recycled paver blocks (Gandhi et al., 2024), flows of newly built floorspace, demolished floorspace, total carbon emissions associated with concrete and emissions per unit floorspace (Eissa and El-adaway, 2024). They have also been used to examine organisational incentive schemes, policy supports, and sustainable development (Ghufran et al., 2022), flows of demolished materials in the economy (Mostert et al., 2022), and in modelling sand and gravel quarry and disposal volumes (Kliem et al., 2021). Thus, stocks and flows diagram prove versatile, not only capturing material flows, but also evolving policy variables (Ghufran et al., 2022).

All these studies considered the temporal evolution of dynamic systems, and subsequent scenarios analysis led to recommendations based on reported metrics (see **Table 5**) and identifying the key leverage points. For instance, Gandhi et al. (2024) identified contractor profit, overhead expenses, and labour costs as the main barriers to using RPBs in India. Eissa and El-Adaway (2024) suggested that a comprehensive CE policy in the US could deliver a 52% decarbonisation potential by 2050, while policy support and incentive schemes have been recognised as key factors for CE transition in Ghufran et al. (2022).

Delay modelling, another key feature of system dynamics, as adopted by Kliem et al. (2021) and Mostert et al. (2022). The CE transition in the construction sector not only requires adequate recycling, but also a constant supply of secondary materials. While Ghufran et al. (2022) considered global participants, all other studies were conducted at the micro or meso-scale. For further information see **Table S8-S9**.

Table 5. Quantified metrics, consideration of 'R' principles in system dynamics applications within the construction sector

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	Reference
Recycled paver block circularity	Manufacturing cost of recycled paver block	Recycle	n.a.	Gandhi et al. (2024)
Decarbonisation potential of US commercial buildings	Annual commercial floorspace, embodied emissions	Reuse, reduce,	n.a.	Eissa and El-adaway (2024)
Policy impacts on CE transition within the construction industry	Policy supports, organizational incentive scheme, and sustainable development	n.a.	n.a.	Ghufran et al. (2022)

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	Reference
Circularity potential of recycled building materials to replace virgin materials	Demand for aggregates for concrete, demand for recycled aggregates for concrete, savings in sand and gravels, unused recycled aggregates	Reduce, recycle	n.a.	Mostert et al. (2022)
Barriers in adopting CE transition in the construction industry	Recycling and recovering quota of CDW and excavation materials, primary gravel price, disposal price	Reduce, recycle, recovery	n.a.	Kliem et al. (2021)

325   n.a.: not applicable

326

3.3 Electrical and Electronics Products Sector

As the name suggests, this sector comprised studies considering electrical and electronic products. It encompassed waste from electrical and electronics equipment (WEEE), batteries, mobile phones, photovoltaics, computer equipment and household white goods. Details about the specific case-study domain can be found in **Table 6** and **Table 7**.

3.3.1 System dynamics modelling in the electrical and electronics sectors

Lähdesmäki et al. (2023) modelled the CE potential of lithium in a global context, while Guzzo et al. (2022b, 2022a, 2021) showed how CE policy interventions facilitated nationwide electrical and electronics waste collection and treatment. Llerena-Riascos et al. (2021) explored the operative-strategic interdependency in improving the representation and performance of waste electrical and electronics equipment (WEEE) collection and processing steps. Salim et al. (2021) delved into socio-technical transition pathways for end-of-life management of rooftop photovoltaic solar panels. In both works Chaudhary and Vrat (2020, 2019) and Sinha et al. (2016) used systems dynamics to investigate circularity regarding mobile phones. Chaudhary and Vrat (2020, 2019) highlighted the drivers for proper circular flow of gold in mobile phones, while Sinha et al. (2016) drew attention to the potential of closing material flow loops in global mobile phone product systems, addressing sustainability challenges of material recovery.

Causal loop diagrams have been key in offering an explicit representation of dynamic interdependencies (Alamerew and Brissaud, 2020; Chaudhary and Vrat, 2020, 2019; Salim et al., 2021), while others presented causality passively (Guzzo et al., 2022a, 2021; Sinha et al., 2016). Facilitation of CE was found to be not only dependent on cost and revenues, but also on strategic regulatory decisions, and proper policy implementation (Alamerew and Brissaud,

2020; Chaudhary and Vrat, 2019). Whereas, circular value-chain mapping of gold, e-waste, and mobile phones with their sustainability benefits were evident in Chaudhary and Vrat (2020, 2019) and Sinha et al. (2016), where sustainability indicators were causally linked. Additionally, inappropriate disposal of hazardous waste was addressed in Salim et al. (2021), urging proper recovery and recycling.

Stocks and flows diagrams were prevalent throughout the literature, effectively representing material flows inside system boundaries. However, Guzzo et al. (2021) used them to represent the flow of technology adoption processes, and Salim et al. (2021) for recycling fund flow. Delay and lifetime distribution modelling through different distributions were shown in Guzzo et al. (2022a, 2022b, 2021). Notably, Guzzo et al. (2022a) presented an inductive-deductive system dynamics model, where the empirical theory was constructed in the inductive stage, and then deductive theory was tested in another case-study.

All the studies reviewed in this sub-section explored the common capabilities of system dynamics modelling - temporal dynamics, scenario analysis, metrics quantification, and thereby recommendations (see **Table 6**). The work of Sinha et al. (2016) was a global-scale study. In scenario analysis, multiple previous scenarios can be superimposed (Guzzo et al., 2021; Lähdesmäki et al., 2023). Specifically, Lähdesmäki et al. (2023) recommended to implement a combined CE policy, informed by such multiple scenarios. Guzzo et al. (2021) suggested the systemic change for CE implementation. While, Salim et al. (2021) found that there were high uncertainties in waste collection, recovery performance, and landfill disposal.

System dynamics can also handle uncertainties of the parameters, and can provide decisions accounting, as shown by Salim et al. (2021). Chaudhary and Vrat (2020) underscored the value of consumer awareness and stakeholder incentives for better CE implementation, while their earlier work (Chaudhary and Vrat, 2019) emphasised the policy interventions for addressing challenges associated with the informal handling of e-waste without environmental and health protection. Meanwhile Sinha et al. (2016) recommended closed-loop recycling through improved collection systems, longer mobile phone retention time, improved recycling in developing countries, and shorter phone hibernation times. This work proposed reducing informal recycling of e-waste, as they claim that it leads to lower resource recovery along with higher pollution. Further details are in **Table S10** - **S11**.

Table 6. Case-study domains, quantified metrics, consideration of 'R' principles, and use of other tools in system dynamics applications within the electrical and electronics products sectors.

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
Waste lithium	Lithium demand by application, lithium content in waste stream, and lithium accumulation	Reduce, refuse, repurpose, remanufacture, recycle, and reuse	n.a.	Lähdesmäki et al. (2023)
Waste from Electrical and Electronics equipment	Material extraction, official EEE collection, inadequate disposal of EEE, ratio of material treated, and ratio of material lost	Reuse, recycle	n.a.	Guzzo et al. (2022b)
Waste from Electrical and Electronics equipment	Official EEE collection, inadequate disposal of EEE, ratio of material treated in last years	Recycle, reuse, recovery	n.a.	Guzzo et al. (2022a)
Waste from Electrical and electronic equipment	Availability of raw material, material extraction, EEE commissioning, total EEE in use, disposal of EEE as WEEE, WEEE recycled	Reuse, remanufacture, repair, recycle, recovery	Bass diffusion model to model the diffusion of technology in the system.	Guzzo et al. (2021)
Waste from Electrical and Electronics equipment	Avoided environmental burden (AEB), repurchase price, WEEE generated, profits	Repair, recycle, remanufacture, recovery	Mixed-integer non-linear programming approach was used to fine tune the system dynamics parameters.	Llerena-Riascos et al. (2021)
EOL management of photovoltaic solar cells	Collection fraction, collection rate, total recovered materials, landfill amount, payback period and number of dwellings with PV	Reuse, repair, recycling, recovery	Quantitative-qualitative triangulation method was used to capture the mental models of the stakeholders.	Salim et al. (2021)
Gold recovery from cell phone recycling	Depletion/savings of gold reserve, gold from E waste, gold from discarded cell phones, economic benefits, environmental benefits, social benefits (job creations), collection efficiency	Reuse, refurbish, recycle, recovery	n.a.	Chaudhary and Vrat (2020)
E-waste reverse supply chain	Depletion of material reserve, material conversion rate, extracted material, economic, environmental, and social benefits, increase of collection coverage, and pre-processing capacity,	Reuse, refurbish, recycle, recovery	n.a.	Chaudhary and Vrat (2019)

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
	demand of recycled materials, change in recycled products with change in refurbish and reuse rate, etc.			
Electric vehicle batteries	Gross benefit of remanufacturing, remanufacturing margin, and price for remanufactured and new electric vehicle batteries	Reuse, remanufacture, repurpose, recycle, recovery	n.a.	Alamerew and Brissaud (2020)
Mobile phone recycling	Gold use by phone manufacturers and gold recovery at the end of life of phone, loop leakage, closed loop efficiency of global mobile phone product systems	Reuse, refurbish, recycle, recovery	Opt Quest optimiser to optimise high and low sensitive parameters.	Sinha et al. (2016)

383 n.a.: not applicable

384

3.3.2 Agent-based modelling and simulation in the electrical and electronics sectors

386 ABMS has been employed to assess the influence of techno-economic and social factors on

387 the circularity of hard-disk drives (HDDs) (Walzberg et al., 2022a). The importance of

388 considering social factors in empirical CE analysis has been underscored, alongside techno-

389 economic considerations (Walzberg et al., 2021). ABMS was also adopted to model waste

390 household appliance recovery (Luo et al., 2019). Mashhadi et al. (2019) stressed that product-

391 service-systems (PSS), such as mobile phone leasing, can overcome CE implementation

392 barriers. ABMS was instrumental in quantifying demand behaviour for circular business

393 models (leasing or functional sales) (Lieder et al., 2017a). Another study by the same authors

394 employed multi-method simulation approach combining ABMS and discrete event simulation

395 (DES) to quantify design efforts for circular options (reuse, remanufacture, and recycle) and

396 supply chain settings (buy-back, pay-per-use, and leasing) (Lieder et al., 2017b). The details

397 of each study and the types of agents can be found in **Table S23-S25**.

398   The ability of ABMS to capture the agents' distinct characteristics, attributes,

399 behaviours, and decision-making rules, i.e. heterogeneity, has been useful in tracking agents'

400 specific CE pathways (Walzberg et al., 2021). By integrating the theory of planned behaviour

401 (TPB) and its associated factors, Walzberg et al. (2022a) determined how the agents'

402 decisions at the individual level led to changes at the systemic level, specifically in their

403 adoption of circular economy (CE) pathways. The heterogeneity of residents, governments,

404 and recycling agents was considered by Luo et al. (2019), who included factors such as waste

appliance generation, industrial standards development, tax incentives, distances from residents, etc.. The 'memorising' capability of agents was demonstrated by Mashhadi et al. (2019) and Lieder et al. (2017a) where previous positive experiences influenced the subsequent decisions regarding adopting CE options (e.g., buying/leasing/pay-per-use, etc.). Meanwhile, heterogeneity demonstrated a single component's four distinct stages (Lieder et al., 2017b): manufactured, assembled in product, disassemble after use, and material recovered.

With more knowledge of the positive impacts of CE, agents can be self-encouraged, i.e. show adaptation. While agents always try to choose a position where their benefits are maximised, the rewards are dependent on the path taken (Luo et al., 2019). Adaptation has been demonstrated due to socio-economic and social status (Walzberg et al., 2022a, 2021), environment-friendly awareness, and peer-pressure (Mashhadi et al., 2019), socio-demographics, social networks, and product utility (Lieder et al., 2017a), and proper marketing and pricing strategy (Lieder et al., 2017b). Complex interactions between agents, and their stochastic natures, were consistently emphasised in each work. ABMS has been employed to represent the flow of materials (Lieder et al., 2017b; Luo et al., 2019; Walzberg et al., 2021), and also spatial considerations (Luo et al., 2019; Walzberg et al., 2021). Meanwhile, agent heterogeneity was obtained from survey data by Mashhadi et al. (2019) and used within an ABMS framework.

Scenarios analysis led to recommendations, as evidenced by metric quantification, for achieving increased circularity (see **Table 7**). For instance, the reuse of hard disk drives was found to be more environmentally friendly (Walzberg et al., 2021). Additionally, CE practice was found to be facilitated by proper education on recycling and recovery options, effective regulatory frameworks, technological innovations, improving product eco-design, and establishment of waste appliance recovery networks (Luo et al., 2019). Scenarios analysis also revealed agents' previous positive experience on buying/leasing affects further buying/leasing decisions (Mashhadi et al., 2019). The *'pay-per-use'* approach supported by advertisements provided environmental friendliness and service-orientation. This was further aligned with a *'buy-back'* scenario for more returns after a certain period in Lieder et al. (2017a).

Table 7. Case-study domains, quantified metrics, consideration of 'R' principles, and use of other tools in agent-based modelling applications within the electrical and electronics products sectors.

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
End of management of magnets of hard-disk drives	Recovered mass of rare earth material (REE), material value, and avoided greenhouse gas (GHG) emission by recycling, hard disk drives (HDD) reuse, and magnet reuse, enhancement of trust towards data wiping.	Reuse, recycle, recovery	Theory of planned behaviour (TPB) was used to model customers' intention to reuse/recycle the hard-disk drives. Data uncertainties and qualities were modelled through data pedigree matrix.	Walzberg et al. (2022a)
Photo-voltaic cell circularity	Recycling costs, material recycling rate, material recovery rate, initial recycling costs, recyclers' net income, reuse rate, landfill costs, societal costs	Recycle, reuse, recovery	Theory of planned behaviour (TPB) was used to model decision-making for PV cell purchase/reuse.	Walzberg et al. (2021)
Waste electrical appliance recovery industry	Waste appliance generated per capita, extent of environmental pollution perceived by residents, service level of each recycler perceived by the residents, residents' recycling tendency with respect to each recycler, recovery rate, policy costs, profits of the agents.	Recycle, recovery	TPB was used to model residents' recycling behaviour.	Luo et al. (2019)
Cell phone leasing	Total buy/lease decision count, tendency to lease next cell phone if the lease term is increased, percentage of leases over time for different new product prices.	Reuse, recycle, recovery	Discrete choice analysis to predict future market demand considering social influences of new product adoption.	Mashhadi et al. (2019)
Washing machine	Number of customers served, aggregated lifecycle cost, aggregated lifecycle impact, and material savings.	Reuse, remanufacture, recycle	Discrete event simulation was used to model the closed loop-supply chain movements.	Lieder et al. (2017b)
Washing machine	Market share, customer satisfaction, price, environment friendliness, service.	Refurbish, reuse, recycle, recovery	n.a.	Lieder et al. (2017a)

n.a.: not applicable

3.4   Circularity of Single Materials

The following sub-section describes the quantification of different aspects of circularity of specific single materials. This covers plastic bottles, platinum, zinc, and copper. While the term plastics itself covers a broad array of materials, Ghosh et al. (2023) considered it as a single material. Note also that no studies were found related to the application of ABMS to quantify circularity of single materials.

3.4.1 System dynamics modelling for circularity of single materials

In a 'learning-by-doing'-based system dynamics model, Ghosh et al. (2023) explored end-of-life pathways for PET bottles, calculating circularity indicators considering technological, economic, and policy constraints. Meanwhile Saidani et al. (2021) employed a multi-method simulation approach to identify, classify and assess key parameters and action levers to close the material cycle loop of platinum in catalytic converters. System dynamics also modelled key endogenous policy impacts on the development of a circular model for zinc manufacturing growth (Ojha and Vrat, 2020), considering exploration, demand, collection, recycling, repair and reuse. Finally, Pfaff et al. (2018) applied system dynamics to examine sectoral primary and secondary copper flows and stocks in Germany.

Causal loop diagrams were presented by Ojha and Vrat (2020) and Saidani et al. (2021) to illustrate the dynamic connections between collection, recovery, circularity rate, and influence of linear and circular economy factors affecting manufacturing output growth. Ghosh et al. (2023) didn't show a stock-and-flow diagram, but conveyed it implicitly to perform the lifecycle and techno-economic analyses, which considered the flow of plastics. Stocks and flows diagrams have been presented to illustrate the flow of platinum (Saidani et al., 2021), zinc (Ojha and Vrat, 2020), and copper (Pfaff et al., 2018). Temporal evolution of material flows was intrinsic in each study. However, spatial aspects were considered less frequently (Ghosh et al., 2023; Pfaff et al., 2018).

With the exception of Saidani et al. (2021), all studies conducted scenarios analysis, leading to recommendations through metrics quantification (see **Table 8**). For instance, optimal PET circularity was when *'recyclate glycolysis'* was adopted with improved collection access, due to increased replacement of virgin materials with recycled resin (Ghosh et al., 2023). Meanwhile, increased geological exploration, improved collection facilities, cost-effective remanufacturing technologies, and better incentive schemes were recommended for improving zinc circularity (Ojha and Vrat, 2020). Finally, Pfaff et al. (2018) concluded that imported primary copper had detrimental environmental impacts. However, this work was contingent on extensive data requirements. See **Table S12-S13** for more details.

475 **Table 8.** Case-study domains, quantified metrics, consideration of 'R' principles and use of
476 other tools in system dynamics applications concerning circularity of single materials.

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	Reference
Plastics (PET bottles)	Circularity (closed loop circularity, open loop circularity, upcycling circularity, incineration circularity, average inflow outflow circularity, landfill diversion circularity) environmental impact (GWP in kg CO_2 eq.) and life cycle costs	Recycle, recover	n.a.	Ghosh et al. (2023)
Platinum in vehicular catalytic converters	Platinum circularity, potential collection, collection of catalytic converters, recovery of platinum	Recycle and recovery	Fuzzy cognitive mapping to identify action levers, drivers, and parameters responsible for loop-closure. Functional analysis system technique (FAST) and matrix impact cross-reference multiplication applied to a classification (MICMAC) to list the potential action levers and to select and cluster the key variables, respectively.	Saidani et al. (2021)
Zinc recycling	Behavioural trends of four variables: green reserve, extraction material, manufacturing output and total refeed for different developed scenarios	Repair, reuse, remanufacture, recycle, recovery	n.a.	Ojha and Vrat (2020)
Copper production and recycling sector	End of life (EOL) collection rate and recycling rate, total copper input to domestic production of finished goods, total collected domestic EOL copper scrap, primary copper input to domestic production of finished goods.	Reuse, recycle, recovery	ASTRA based macroeconomic model was combined with system dynamics to evaluate the economic aspects of the sector.	Pfaff et al. (2018)

477 n.a.: not applicable

478

479 ## 3.5 Manufacturing Sector

480 The following sub-section describes the applications of system dynamics as a modelling
481 approach to quantify the aspects of circularity related to manufacturing. While this sector
482 covered, amongst others, household white goods and electrical motors, the focus of the
483 studies was on the manufacturing or remanufacturing process. No articles were found related
484 to the use of ABMS for circularity quantification in this sector. Details about the domain can
485 be found in **Table 9**.

3.5.1 System dynamics modelling applications in the manufacturing sector

A multi-method simulation approach was proposed for a circular manufacturing system (CMS) of washing machines (Roci et al., 2022), integrating ABMS, discrete event simulation (DES), and system dynamics modelling. Franco (2019) demonstrated the impacts of product design (i.e., slowing resource flows through design for longevity, ease of maintenance and repair; and by design for disassembly and recycling), business models (i.e., slowing resource flow by product-service-system and maintenance, and reuse), and post-use strategies on facilitating CE. In a theoretical study on data-driven circular economy Charnley et al. (2019) developed the concept of certainty of product quality (CPQ) and applied it to electric motor circularity through remanufacturing, by integrating DES and system dynamics modelling.

Neither Charnley et al. (2019) nor Roci et al. (2022) developed causal loop diagrams, but they have been presented to highlight the causality between different indices (e.g., disassembly index, recyclability index, functional risk, etc.). Stock-and-flow diagrams accounted material flows (Charnley et al., 2019; Franco, 2019), as well as dynamic evolutions of finance, and emission flows (Roci et al., 2022).

With Austria as their system boundary, scenarios analysis and recommendations driven by metrics quantification revealed the benefits of circular economy for washing machines (Roci et al., 2022) (see **Table 9**). The work also found that manufacturing cost dominated lifecycle costs, followed by installation, refurbishment, and deinstallation costs. However, environmental impact was dominated by the use phase, possibly due to the long lifespan of white goods. Franco (2019) observed that when perceived functional risks of recycled or reused products were low, it positively impacted circularity. Additionally, increased CPQ was helpful in promoting the CE as shown in Charnley et al. (2019). See **Table S14-15** for more information.

Table 9. Case-study domains, quantified metrics, consideration of 'R' principles and use of
other tools in system dynamics applications within the manufacturing sector.

Domain of case-study	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	Reference
White goods manufacturing	Lifecycle costs, environmental performance (kg CO_2 eq.), revenue streams and profit over time.	Reuse, refurbish, recycle, recovery	ABMS was adopted to describe the heterogeneity of the agents (i.e., manufacturers, customers, etc.). DES was utilised to describe the processes flow (e.g., manufacturing processes and logistic activities).	Roci et al. (2022)
Hypothetical manufacturing firm	Products collected for recycling, recycled products inventory, recycling waste rate, recycling rate, recycled products sales rate, purchase rate, products in use, landfill products, products collected for recycling, etc.	Repair, reuse, refurbish, recycle	Bass diffusion model was adopted to model the shape of the distribution of the short and long-life product.	Franco (2019)
Remanufacturing process of electric motors (rotor and shaft)	Time spent for remanufacturing based on the certainty of product quality (CPQ) value, effect of CPQ on reusable products.	Reuse, repair, refurbish, recovery	DES for enumerating the sequence of operations in a remanufacturing process.	Charnley et al. (2019)

3.6 Industrial Symbiosis

Industrial symbiotic networks (ISNs) represent clusters of firms engaged in exchanging
residual materials, energy, and information, with the overarching goals of fostering economic
prosperity, social advancements, and mitigating environmental impacts. They have been
considered as 'complex adaptive systems' for compelling reasons: actors emerge into
coherent forms over time, their adaptive nature reflecting their ability to change over time,
self-organisation because of their ability to find new partners and collaborations based on
mutual utility, path-dependency and non-linearity (Fraccascia and Yazan, 2018).

3.6.1 System dynamics modelling in industrial symbiosis

While ABMS is considered as more adept at capturing symbiotic patterns with heterogeneous
agents in ISNs, some authors tried to model it through system dynamics models. A dynamic
empirical evaluation model for capturing sustainable development of eco-industrial parks was
introduced by Zhao et al. (2023), using an emergy index. Meanwhile, Morales et al. (2022)
modelled a meso-scale CE implementation for bio-based industrial symbiosis (BBIS) of the

sugar-beet value chain, emphasising the concept of viable value chain (VVC) during disruptive events (e.g., COVID-19, climate change). In a different context, Dong et al. (2017) proposed a system dynamics model to understand the long-term materials flow inside a coal power plant and a cement production plant for integrated circularity.

The inclusion of a causal loop diagram in Zhao et al. (2023) facilitated capture of the dynamics of different industrial sectors. Causality of economy and ecology by sharing of the (waste) materials was presented in Dong et al. (2017). The concept of emergy consists of money, material, and energy flows, and either or both were captured through stocks and flows diagrams in all studies.

Table 10. Case-study domains, quantified metrics, consideration of 'R' principles in system dynamics applications for the manufacturing sector.

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
Eco-industrial park	Economic development (EDR[1], EYR[2]), environmental compatibility (EWR[3], ELR[4]), social acceptability (ED[5], and CP[6])	Not mentioned.	n.a.	Zhao et al. (2023)
Sugar-beet value chain	Sugar production, CO_2 emission, stillage, and bioethanol production	Recycle	n.a.	Morales et al. (2022)
Cement and coal production plant	Natural resource saving (e.g., gypsum, clay, limestone, coal consumption, water consumption), reduction of pollutants (SO_2, smoke dust emission), carbon emission from calcination, costs savings, sales revenue, increase of costs of water, supply demand difference (SDD) of fly ash, de-sulphurised gypsum and slag generation, electricity power yield, cement yield	Reduce, recycle, repurpose, recover	n.a.	Dong et al. (2017)

n.a.: not applicable

1. EDR is the ratio of total emergy use and industrial added value of the park in one year.
2. EYR is the ratio of the total emergy output to the emergy purchased from society (e.g., fuels, goods and services).
3. EWR is the ratio of the sum of emergy, with three wastes (viz., waste gas, wastewater, and solid waste) to the total emergy, which was used to measure the pressure of wastes on the ecosystem.
4. ELR is the ratio of purchased and non-renewable local emergy to the free/renewable resources emergy.
5. ED is the ratio of emergy created by production processes to the area of the eco-industrial park.
6. CP is the ratio of available and per capita emergy usage.

All of these studies considered system boundaries at the meso-scale and included temporal dynamics. Through scenarios analysis, and metrics quantification (see **Table 10**) these studies provided insights for decision-making. Zhao et al. (2023) adopted a science and technology-driven scenario to deliver optimal sustainable development. Systematic consideration of the value chain in industrial symbiosis to prevent supply chain collapse during shocks was underscored in Morales et al. (2022), with their forecasts unveiling complexities overlooked by linear economic models. Meanwhile, efficient supply chain eco-design emerged as critical for circularity of two mutually dependent sectors (Dong et al., 2017). See **Table S16 – S17** for details.

3.6.2 Agent-based modelling and simulation in industrial symbiosis

ABMS modelled actors' behavioural patterns (viz., waste suppliers, waste processor), and their intricate relationships towards ISN robustness (in terms of network survival for a particular time period, and cash flows per tonne of waste) (Lange et al., 2021a). While the viability of ISN survivability was examined for two business models (Lange et al., 2021b), namely circular waste management and waste as by-product. The dynamics of the construction supply chain, focusing on recycled concrete aggregate in an ISN was presented by Yu et al. (2021). Geographically oriented symbiotic relationships were examined in Raimbault et al. (2020), and material flows in a complex stakeholders' involvement network in Fernandez-Mena et al. (2020a, 2020b). Several aspects of ISN survival through information sharing (Fraccascia and Yazan, 2018), cost-sharing negotiations between companies (Yazan and Fraccascia, 2020), redundancy strategy (Fraccascia et al., 2020), and the impact of online platforms (Fraccascia, 2020) have been shown.

Agent heterogeneity (**Table S27**) has been captured in terms of changing supply chain quantity, physical degradation of waste and chemical composition (Lange et al., 2021a, 2021b). Agents were also heterogeneous in terms of their quantity, location, storage capacity, material flow rate (destination agent), and various attributes for *'vehicle'* agent (Yu et al., 2021), and through their demand-offer functions (Raimbault et al., 2020). Finally, agents were heterogeneous due to industry type plus waste processor (Fernandez-Mena et al., 2020a, 2020b) or input-output characteristics (Fraccascia, 2020; Fraccascia et al., 2020; Fraccascia and Yazan, 2018; Yazan and Fraccascia, 2020).

579   Emergent patterns due to agents' adaptation capability ranged from leaving an ISN

580   network (Raimbault et al., 2020), choosing new partners (Lange et al., 2021b), and navigating

581   uncertain encounters with the environment (Fraccascia et al., 2020). Materials flow

582   (Fernandez-Mena et al., 2020a, 2020b), and cash flow (Lange et al., 2021b) between agents

583   have also been quantified. In Raimbault et al. (2020), and Yu et al. (2021) material flows

584   were modelled stochastically. The spatial dispersions of the agents (Fernandez-Mena et al.,

585   2020a, 2020b; Yu et al., 2021) were also contemplated through ABMS, proving beneficial

586   over system dynamics.

587   The memorising capability of agents in ABMS was showcased through 'fitness to

588   process the waste', 'leaving threshold' in Lange et al. (2021a). A similar 'fitness function',

589   based on economic benefits, encouraged agents to stay in ISNs (Yazan and Fraccascia, 2020).

590   How the agents' activities were triggered by realising the material transfer from the vehicle

591   partner was presented in Yu et al. (2021). Note that, unlike with system dynamics, all the

592   agents in the ABMS are not required to function during the entire simulation period. For

593   instance, allocation of materials to agents only when they have the capacity to accommodate

594   it (Fernandez-Mena et al., 2020a).

595   Scenarios analysis, leading to recommendations through metrics quantification (see

596   **Table 11**) was conducted across most studies, apart from (Lange et al., 2021a; Raimbault et

597   al., 2020). Notably, changes in scenarios in ABMS allowed observations at both micro and

598   system levels, presenting its unique advantage over system dynamics. Additionally, during

599   scenario analysis in ABMS, new emergent patterns could develop, which is not the case in

600   system dynamics modelling. For instance, economic behaviour preceded behavioural

601   patterns, such as ISN partners leaving networks due to insufficient waste supply (Lange et al.,

602   2021b). Yu et al. (2021) suggested that increasing upcycling efficiency and subsiding

603   stakeholders plays a pivotal role in RCA circularity. Distances between agents were key for

604   ISN survival (Fernandez-Mena et al., 2020a; Raimbault et al., 2020). A circularity scenario

605   has been reported to mitigate GHG emissions, but at a substantial trade-off between food

606   production and livestock number (Fernandez-Mena et al., 2020b). Sensitive information

607   sharing through gradual trust-building was emphasised in Fraccascia and Yazan (2018).

608   Minimising the differences between input-output quantities of waste facilitated the ISN

609   survivability (Yazan and Fraccascia, 2020). Transaction cost played a pivotal role in

610   economic and environmental benefit provided by ISN (Fraccascia et al., 2020). While

611   Fraccascia (2020) found that when over 60% of ISN members engaged with online platform

612   sharing, partners who did not participate in the ISN were disadvantaged, and adversely

613   impacted the environmental performance. For more information, see **Table S26 – S28**.

614   **Table 11.** Case-study domains, quantified metrics, consideration of 'R' principles and use of
615   other tools in agent-based modelling applications for industrial symbiosis.

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
ISN partners: (a) large scale agricultural area, (b) small-scale urban agricultural area focused on sustainable food production and recreation, (c) a business park	Cash flow per each industrial symbiotic network actor, and failure or success of network (robustness).	Recycle, recovery	Theory of planned behaviour (TPB) was used to model agents' negotiation and self-evaluation process.	Lange et al. (2021a)
Bio-based material suitable for anaerobic digestion for processing local waste and energy production from biogas	Circular business model survival rate percentage, value captured or lost per actor for each of the scenario.	Reuse, recovery	TPB was used for bilateral negotiations between waste processor and suppliers.	Lange et al. (2021b)
Recycled concrete aggregate ISN	Delivered recycled concrete aggregates, reduced CO_2 emissions, and space of cooperation/industrial symbiosis probability between firms involved in the network for different scenarios.	Reuse, recycle	GIS was adopted to articulate the complex spatial relationships of industrial actors.	Yu et al. (2021)
Hypothetical symbiotic network	Total waste flow and relative cost.	n.a.	Multi-objective optimization was adopted to minimize the cost and waste products given that agents were distributed in a different geographical location.	Raimbault et al. (2020)
Agro-food network	Nitrogen flow, CO_2 emissions, number of local flows, CO_2 eq. emitted per gigagram of protein and tera-calorie of metabolizable energy in food production, crop production, meat and milk production, animal feeding district balance, biogas, and electricity production.	Reuse, recycle and recovery	GIS was adopted to highlight the distances between the agents.	Fernandez-Mena et al. (2020a)
Agro-food network	Different local material flows within the network (e.g., local fertilization flow, animal requirements flow, and energy flows), the average distance in exchanges of manure and grass,	Reuse, recycle and recovery	Multi-criteria assessment to compare the performances of different scenarios.	Fernandez-Mena et al. (2020b)

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
	and the CO_2 emission from material transport.			
Hypothetical industrial symbiosis case studies comprising marble waste and concrete production, and alcohol slops used for fertilizer production	Percentage of waste exchange by each company involved in the IS, platform usage rate, and amount of saved residuals.	Reuse, recycle and recovery	n.a.	Fraccascia (2020)
A hypothetical marble-concrete industrial symbiosis case-study	Economic performance indicator $(\frac{economic\ benefits\ created\ by\ IS}{production\ costs\ of\ firms})$, and environmental performance measure $(\frac{total\ waste\ diverted\ from\ landfill}{primary\ inputs\ saved+total\ waste\ produced+required\ primary\ inputs})$,	Reuse, recycle and recovery	n.a.	Fraccascia et al. (2020)
A hypothetical marble-concrete industrial symbiosis case-study	Economic benefits, probability of implementation of industrial symbiosis.	Reuse, recycle and recovery	n.a.	Yazan and Fraccascia (2020)
Hypothetical industrial symbiosis case studies comprising marble waste and concrete production, and alcohol slops used for fertilizer production	Economic performance indicator $= (\frac{economic\ benefits\ created\ by\ IS}{production\ costs\ of\ firms})$, and environmental performance measure $= (\frac{total\ waste\ diverted\ from\ landfill}{primary\ inputs\ saved+total\ waste\ produced+required\ primary\ inputs})$	Reuse, recycle, recovery	Physical and monetary flows were modelled through enterprise input-output analysis (EIOA).	Fraccascia and Yazan (2018)

n.a.: not applicable

3.7 Miscellaneous Sectors

This section covers a range of studies which we were unable to allocate to any aforementioned sector. Details about the domain of application can be found in **Table 12** - **Table 13**.

3.7.1 System dynamics modelling applications in miscellaneous sectors

Territorial competitiveness index (TCI) has emerged as a significant metric for gauging sustainable growth. Sezer et al. (2024) projected the development trajectory of Izmir in Turkey through TCI. In (Viruega Sevilla et al., 2022), authors showed the system of waste oil flow in the motor industry and its circularity. Meanwhile, recognising the role of extended producer responsibility towards promoting CE, Kuo et al. (2021) developed a system dynamics model to determine the optimal subsidy (i.e., minimisation of cost and maximisation of recycling rate) between stakeholders pertaining to aseptic paper packaging. A parallel approach has been adopted to quantify and evaluate the implementation and

631 effectiveness of regional CE (Gao et al., 2020). Tracking material and energy flows between

632 industries considering the impact of environmental fragility-economic poverty vicious cycles

633 (FPVC) were shown in Cheng et al. (2019). Additionally, Asif et al. (2016) developed an

634 integrated ABMS and systems dynamics approach to understand the dynamic relationships

635 between business approaches, supply chains and product-design, along their influences on

636 economic and environmental performance.

637 Causal loop diagrams outlined the causal interplay between sustainability indicators

638 and TCI in Sezer et al. (2024). A similar diagram was utilised in Kuo et al. (2021) to

639 represent the dynamics of waste generation, incorporating interventions related to production,

640 costs, and recycling. When the multiple metrics for a particular value domain in CE is

641 considered, there are always some cross-domain interconnectedness as presented in Asif et al.

642 (2016) and Gao et al. (2020), where resource consumption subsystem, environmental impact

643 subsystem, etc. were causally linked.

644 With the exception of Sezer et al. (2024), all studies in this sub-section developed

645 stocks and flows diagrams to represent material flows. Sezer et al. (2024) used it for showing

646 the accumulation of GDP growth, alongside material flows (i.e., waste generation). Temporal

647 consideration was integral in all studies, leading to scenarios analysis and recommendations

648 through metrics quantification (see **Table 12**). For instance, Sezer et al. (2024) projected a

649 peak of TCI in 2020, followed by a moderate decline to 2022, then a subsequent rise to 2027,

650 due to development of sustainable policies, efficient resource utilisation, GDP increase, etc.

651 Similarly, in (Viruega Sevilla et al., 2022) authors used stocks and flows diagram to show the

652 flow of waste oil in the motor industry. While, Kuo et al. (2021) identified collection cost and

653 recycler capacity were the most sensitive parameters in the system, highlighting the

654 decreased collection costs increased EPR fund generation, and decreased recycler capacity

655 led to increased landfilled waste. Gao et al. (2020) identified that, along with growth of CE,

656 GDP also increased, contingent to slight decrease in birth rate and development of tertiary

657 industries. Cheng et al. (2019) showed that CE improved the ecological and economic

658 benefits in terms of improved livelihoods and reduced pollution of the considered system. For

659 more information, see **Table S18-S19**.

Table 12. Case-study domains, quantified metrics, consideration of 'R' principles and use of other tools in system dynamics applications for miscellaneous sectors.

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
Sustainable development of a city in Turkey	Annual GDP growth rate, social well-being, sustainable land use, CO_2 emission, renewable energy production, technology innovation index, waste generation, and territorial competitiveness index.	Reuse, reduce, recycle, recover.	n.a.	Sezer et al. (2024)
Motor industry residues (waste oil, spent solvent, battery waste, and dirty wipes)	Outflows of waste oil, emissions (CO2), human toxicity, energy cost	Recycle, recovery	n.a.	Viruega Sevilla et al. (2022)
Aseptic paper packaging waste	Collection rate, recycling rate, extended producer responsibility fund, collection flow, recycling flow and waste in landfill	Recycle, repurpose	n.a.	Kuo et al. (2021)
Regional CE of Guangdong province in China	Mass of total and direct material input and output components, Resource consumption and waste emission (biological substance consumption, fossil fuel consumption, solid waste consumption), intensity efficiency index (total material input of 10,000 RMB of GDP, and total material output of 10,000 RMB of GDP), building material consumption, and industrial exhaust emission	NA	n.a.	Gao et al. (2020)
A meso-scale implementation of a FPVC area in China	Benefits of livestock faeces recycling (e.g., biogas production rate, recycling amount of faeces, conversion amount of organic fertilizer, pollution free fruits and vegetables output), effects of water savings (e.g., water saving amount, annual recycling of wastewater, terrace area, total number of water cellar), effects of waste recycling (e.g., utilization amount of potato residue, annual straw utilization and burning, mulching fil remained, feeding beef cattle), effects of energy savings (e.g., fossil energy decreases, CO_2 emissions reduction).	Reduce, reuse, recycle, repurpose, recovery	n.a.	Cheng et al. (2019)
Circular product systems	Environmental performance, cost-based economic performance, and profit-based economic performance.	Remanufacturing, reuse, recycle	ABMS was coupled with system dynamics to capture the market information (population, income of the population, etc) and offer attributes (price	Asif et al. (2016)

Case-study domain	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
			to offer, convenience of the offer, etc.)	

662 n.a.: not applicable

663

3.7.2   Agent-based modelling and simulation applications for miscellaneous sectors

665 ABMS has been adopted to examine circularity of wind power generation, considering end-
666 of-life options for turbine blades (Walzberg et al., 2022b). Whereas, circularity via fashion
667 renting, i.e., a product-service system has been examined using ABMS to represent
668 customers' behaviour and interactions (Fani et al., 2022).

669   Both studies showed the heterogeneity of agents in terms of behaviour. This led to
670 different paths for material circularity. With theory of planned behaviour (TPB) used to
671 represent the behaviours of the agents', ABMS was crucial in representing how micro level
672 changes of the TPB parameters impacted the whole dynamics of the system. In each study, all
673 of the agents were interconnected, and connected with the environment. Changes in any of
674 them led to the emergence of new behavioural patterns to adapt them in the system. Spatial
675 and temporal considerations were inherent, along with the stochastic natures of the agents.
676 The quantified metrics are shown in **Table 13**. Furthermore, Walzberg et al. (2022b) found
677 that regulatory pressure and attitudes positively impacted recycling, and agents were more
678 prone to recycle when the recycling facilities were located close-by. For more information,
679 see **Table S29-S31**.

680 **Table 13.** Domains of case-studies, quantified metrics, consideration of 'R' principles, and
681 use of other tools in agent-based modelling applications for miscellaneous sector.

Domain of case-study	Metrics and/or parameters quantified	Which 'R's were considered?	Use of other tools	References
Onshore wind turbine blades circularity	Regional cumulative mean landfill rate according to different transportation costs, landfill behaviour under logistic barriers, adoption of thermoplastic blade design and the dissolution recycling pathway.	Reduce, reuse, repurpose, recycle	TPB was adopted to represent agents' behaviour and its effects on the neighbouring agents.	Walzberg et al. (2022b)
Fashion renting process	Customers' attitude towards fashion renting, performance of the service store, and experience of the customer.	Reuse, refurbish, recovery	DES was used to model the fashion renting process.	Fani et al. (2022)

4   Critical Observations

This section examines a number of key themes highlighted by this study. It starts by examining the major themes considered by both system dynamics and agent based modelling and simulation; comparing and contrasting their application. It then discusses the metrics assessed by each of the modelling approaches, before considering the external tools used with each modelling approach. Finally, it considers which of the 'R'-based frameworks are considered by each technique and in each sector. The section is not intended as a critical analysis of circularity, but rather of the modelling tools used for circularity quantification.

4.1   Major Themes of System Dynamics and Agent-Based Modelling and Simulation Approaches

4.1.1   Why is system dynamics modelling favoured in CE quantification?

The preferences of system dynamics modelling in quantifying CE can be attributed to several key themes identified in the earlier discussions. These themes encompass causal loop diagrams, stock and flow diagrams, consideration of non-linearity or unpredictable variable evolution, temporal scale, spatial considerations, delay modelling, scenario generation and recommendations achieved through quantification of metrics.

A circular economy system is naturally complex, with lots of uncertainty and variability due to its constantly changing patterns. Thus, organisations seek an approach that can model systems and analyse their behaviour before actual implementation. System dynamics has both qualitative and quantitative analysis capabilities (Sumari et al., 2013). The qualitative capability is exemplified through causal loop diagrams (e.g., reinforcing and balancing) to account for the causal relationships between system variables. Quantification involves the transformation of causal loop diagrams into stocks and flows diagrams. The usual workflow for developing a system dynamics model is shown in **Figure S1**. It shows that initial models often cannot capture reality, and system dynamics modelling is therefore an iterative approach, where the model is continually updated based on inputs from the system thinker. This was clearly stated by Sterman (2000).

The stock and flow diagrams in the literature are not only being used to represent the flow of materials, but also to model flow of money, energy, policy variables, etc. The diagrams represent the aggregation and disaggregation of stocks and flows in a continuous time domain through various differential equations, accounting for the causality of other

system variables. Thus, compared to dynamic MFA by system dynamics models, static MFA and Bayesian MFA do not allow extrapolation and exploration of future scenarios, but they rather provide snapshots of systems at a given time, and do not consider non-deterministic causality and/or interdependency of other system variables. However, this aggregation in a continuous time domain leads to loss of individual properties, and a perfect mixing condition becomes prevalent in terms of dynamic MFA (Guerrero et al., 2016). The (commercially) established/ standardised dynamic MFA performing platforms, often associated with life-cycle assessment approaches (e.g., STAN, Umberto, and OpenLCA, SimaPro) do not consider the internal dynamics within the system.

Additionally, stocks and flows within any circular economy system (or complete value-chain) may be a stop-start process. For example, products may stay in a process, e.g., use phase, for some period, causing delays. This delay modelling is a unique characteristic of system dynamics modelling and has been incorporated either stochastically or deterministically (Guzzo et al., 2021). This delay modelling can give rise to non-linearity, as can causal loops; where one parameter may have a non-linear relationship with other parameters, in turn affecting stocks and flows. Each of the subsections have shown examples of system dynamics being used to demonstrate changes over time.

While both ABMS and system dynamics can perform spatial analysis, the former requires more, finer system details than the latter. Conversely, the aggregation property of the latter provides decisions at a system level and may not provide finer details at the local level. While finer details may be possible, this comes at the cost of increased computational complexity.

4.1.2 Why is agent-based modelling and simulation favoured in CE quantification?

The ABMS literature revealed major themes: heterogeneity, adaptation, agent-agent and agent-environment interactions (sometimes leading to emergent properties), spatial considerations, flow modelling, stochasticity of agents and scenarios analysis.

In terms of individuality modelling, ABMS is superior to system dynamics as it can handle finer details (Borshchev and Filippov, 2004). The memorising capability of ABMS leads to adaptation potential through path dependency. In other words, if agents are rewarded for following a particular path, then their future behaviour is more likely to also follow that particular path. This rewarding information is sometimes shared with neighbouring agents. Thus, discrete-time disaggregated agents interact with each other and/or their environment at

746   each time-step, and based on pre-defined state-chart rules, they either move to the next state

747   or stay in the current state. The interaction space between agents is usually user-defined (e.g.,

748   circle (Fernandez-Mena et al., 2020b)) and can be adjusted as per the case-study (Guerrero et

749   al., 2016). Furthermore, some interesting phenomena in the context of CE systems, such as,

750   technology adoption, word-of-mouth, and residents' intention lends authors to ABMS.

751   Although these can be modelled with a system dynamics approach, it is at the cost of time

752   and complexity (i.e., by incorporating different variables and thereafter setting their values

753   and causal relationships).

754   Another benefit of ABMS for simulating CE scenarios is its capability to incorporate

755   the spatial scale. This has been attempted with a spatial system dynamics model (Neuwirth

756   and Peck, 2013), (in different context) by integration of the GIS system in the model, but its

757   use is still not widespread. As shown in **Section 3.6.2** and in Raimbault et al. (2020), the

758   clustering of industrial symbiotic partners is highly relevant to circular economy systems at

759   the meso- (regional) or macro- (national or global) scales.

760   The delay modelling in system dynamics and triggering of a particular event in ABMS

761   are ostensibly analogous, but quite different in mechanism. While the former is part of the

762   model's internal process and is governed by mathematical equations, the latter signifies the

763   activation of a particular agent, governed by rules. Furthermore, the former does not produce

764   emergent properties, rather it influences the flows, while the latter may produce emergent

765   properties, but cannot be predicted in advance. Thus, depending on the rules, which are

766   generally stochastic in nature, an event is triggered in the ABMS, while at the system level

767   properties are generated.

768   Conversely, ABMS can deal with qualitative data which may be represented in terms of

769   scale values. For instance, considering the technological yield increase probability and

770   attention to social reasoning as discrete values between [0,1] (Farahbakhsh et al., 2023) and

771   incorporating these in simulations and scenario analysis. Thus, when such parameters are not

772   easily quantifiable, ABMS can be considered a suitable approach.

773   Scenario analysis in system dynamics and ABMS yield are both feasible, but from

774   different perspectives. While system dynamics considers aggregate properties at the system

775   level, in ABMS emergent properties are observed, which are in turn dependent on the agents

776   and their dynamic interactions with each other and their environment. System dynamics

777   scenario analysis often yields results from a single simulation run for a given parameter set,

778   while ABMS typically requires multiple iterations to account for stochasticity and derive

779   robust calculations. To elaborate, a single simulation run in system dynamics provide a

780   complete picture of the system's behaviour for a given set of initial conditions and

781   parameters. However, the scenario analysis through system dynamics requires multiple

782   parameters' adjustments, which in turns require to re-run the model with the adjusted

783   parameters to get the complete understanding of the system. Thus, each scenario typically

784   involves a deterministic simulation unless uncertainty is explicitly incorporated. However, in

785   ABMS, due to stochasticity of the individual agents, and their associated rules, the system is

786   itself stochastic. To understand the system's behaviour, multiple iterations or simulation are

787   required to account for the variability and derive statistical properties (e.g. confidence

788   intervals).

4.1.3   Flow consideration through system dynamics and agent-based modelling and

790   simulation

791   Flows are critical to revealing circularity, be they materials, energies, money, or policy.

792   However, their modelling in ABMS and system dynamics models differ, as the former retains

793   individuality, while it is lost in system dynamics, as shown in **Figures 3a-3b** (considering the
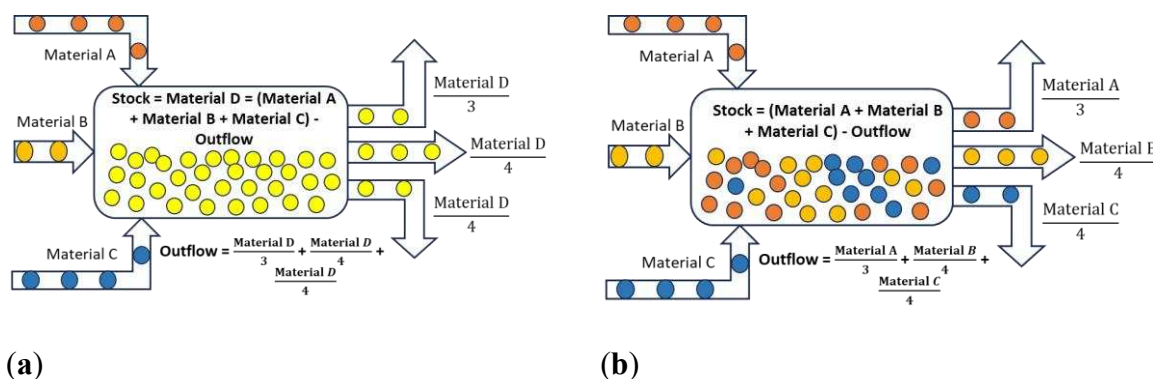
794   example of material flows).

795

(a)   (b)

796   **Figure 3: (a)** Materials flows in system dynamics modelling approach; and **(b)** Materials

797   flows in ABMS approach. Materials identity is lost in SD models but retained in ABMS

798   modelling, as indicated by the colour visualisation.

799

800   Examining the papers in this study more closely highlighted a significant aspect.

801   Boundaries conditions are a vital component of life cycle assessment, social life cycle

802 assessment, and life cycle sustainability assessment. While CE modelling through system

803 dynamics and/or ABMS can adopt proper steps to select system boundaries as per the cut-off

804 criteria, as well as clear identification between elementary flows, reference flows, etc., these

805 were absent from all the reviewed studies in this article. It should be imperative that the

806 modeller identify and report the key aims and objectives of any CE system modelling. This

807 will enable the proper modelling approach, plus coupling value metrics with flow modelling.

808 To explain further, consider the work of Walzberg et al. (2021), where agents were

809 triggered in the material exchanges by economics or peer pressure. Additionally, at each

810 time-step the agent decided whether the waste material was landfilled or recycled, based on

811 the cost-constraint. Similarly, in Raimbault et al. (2020), at each time-step, each agent looked

812 whether their waste outputs could be another agent's input. They then considered spatial and

813 economic perspectives (because increased inter-agent distances increased associated

814 transportation costs). Only if these requirements were fulfilled, did material exchange take

815 place. Conversely, material exchange in Fernandez-Mena et al. (2020b) was completely

816 stochastic in nature, because the preference coefficient was not given as an input by the

817 modeller but randomly selected by the simulator. Thus, ABMS modelling, considers material

818 exchange both from the micro-level perspective, but also after meeting various criteria. While

819 this can also be modelled by system dynamics models, it is at the cost of modelling

820 complexity.

821 **4.2 Joint Consideration of Metrics through System Dynamics and Agent-Based**

822 **Models**

823 CE has been considered a practical approach to progress towards a sustainable future

824 (Geissdoerfer et al., 2017; Kirchherr et al., 2017), adopting the three pillars of sustainability,

825 as first proposed by Brundtland – economic gains, cleaner environment, and societal

826 prosperity (Brundtland, 1987). **Figure 4** shows how various studies in the different sectors

827 considered 'value'-associated metrics from each of these three pillars. Half of the studies

828 considered more than one metric, yet only around 10% considered value metrics covering all

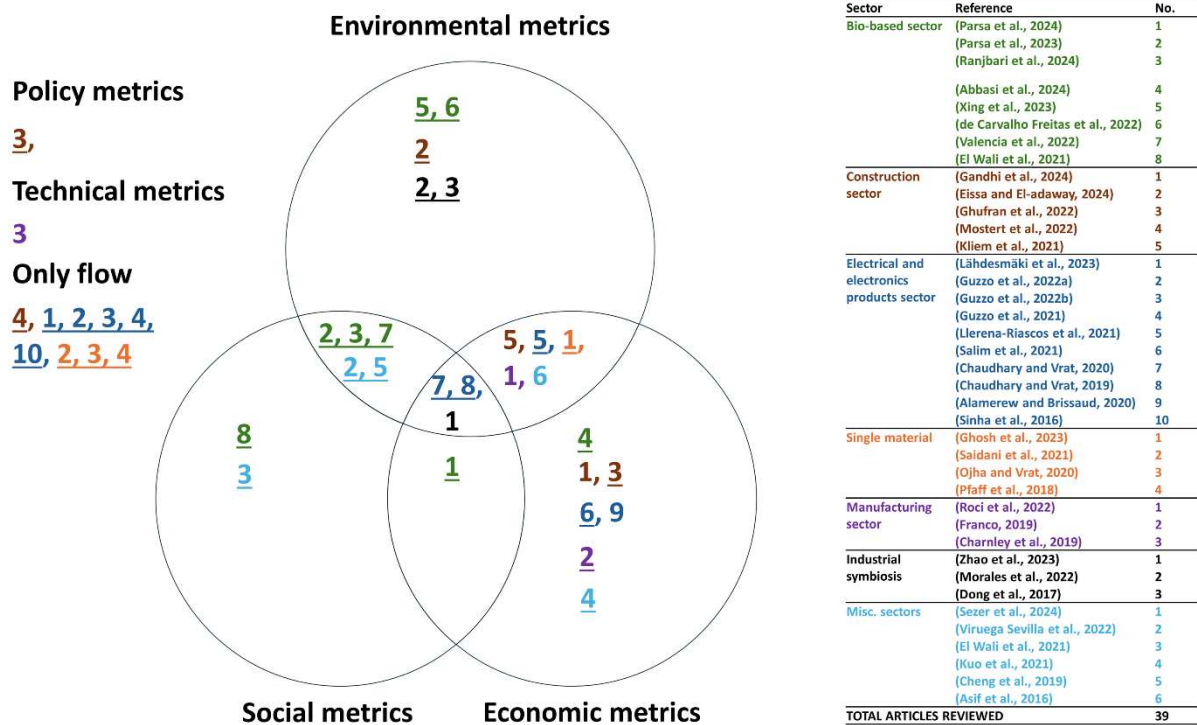829 three of environmental, economic and social domains.

Figure 4. Consideration of different circularity metrics in system dynamics studies. The colours reflect the different sectors, while studies considering 'flow' are shown as underlined. Apart from the two studies in electrical and electronics products sector, and one study in industrial symbiosis sector, none of the reviewed system dynamics studies jointly considered the quantification of environmental, economic, and social metrics.

Overall, most studies focused on economic and then environmental aspects. However, there were differences between sectors. Studies in the bio-based sector had a greater emphasis on social and environmental metrics, while studies in the electrical and electronics sectors had a greater emphasis on economic aspects. Most of the studies considered flow metrics jointly with other metrics' groups, but five studies from electrical and electronics products sector, three from single material sector, and one from construction sector focused on quantification of the flow metrics only.

Similarly, the metrics studied by ABMS can be grouped into economic, environmental, social value, others, and MCP flows (**Figure 5**). Focussing on environmental, economic, and social value metrics, economic metrics dominated, followed by joint consideration of environmental and economic metrics, and environmental metrics. Meanwhile, only one study, in the electrical and electronic products sector, considered social aspects, in conjunction with economic metrics. While about half of the system dynamics studies considered multiple metrics, far fewer ABMS studies considered more than a single metric. Aside from studies in

852   the electrical and electronic products sector only one study, in the bio-based sector,

853   considered more than one metric. However, the presence of miscellaneous metrics not related

854   to circular economy metrics become prominent in this group. Furthermore, none of the

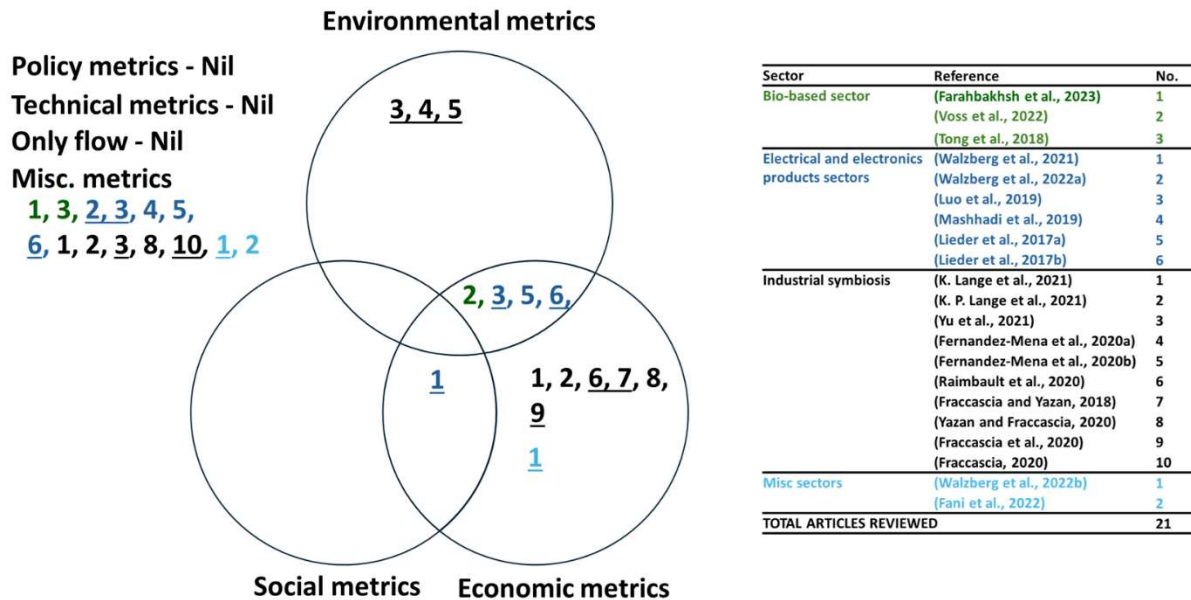855   studies considered policy, technical or flow alone metrics.

856
857

Figure 5. Consideration of different circularity metrics in ABMS studies. The colours reflect the different sectors, while studies considering MCP flow are underlined. None of the reviewed ABMS studies jointly considered the environmental, economic and social metrics.

862

863   The dominance of single value metric studies using ABMS can be understood by

864   recognising that this approach is mostly focused on how the changes in the micro level

865   agents' behaviours impact the whole system. Possibly, researchers have avoided to jointly

866   quantify the CE value metrics through ABMS due to increased computational complexity and

867   traceability of models' microstructures.

868   However, describing circular economy requires a holistic approach, where overall

869   economic, environmental and social benefits must be quantified from the systems thinking

870   perspective for informed decision making. This enables targeted policy implementation

871   through identification of key leverage points of the whole system. Furthermore, while

872   analysis of individual systems has proved useful, these systems have still been somewhat

873   isolated from a global perspective, and there have been limited endeavours to couple them

874   and quantify metrics from a global perspective. This is possibly because there is, as yet, no

875 global consensus on quantification of circular economy value metrics (Hossain et al., 2024;
876 Mani et al., 2025; Negrete-Cardoso et al., 2022). Furthermore, value optimisation at key
877 leverage points in the various systems considered here, is missing.

878

4.3 Utilisation of External Tools along with System Dynamics and Agent-Based Modelling and Simulation

881 System dynamics can be considered as both rigid and flexible in its approach. It is rigid in
882 terms of maintaining its fundamental principles as outlined in **Table S1**, yet flexible in terms
883 of its integration capability with other analytical tools. The inputs to the model can be
884 optimised or tweaked, but there can be no changes in the basic principles of a system
885 dynamics model. Meanwhile, outputs from system dynamics models can be further analysed
886 using other tools, for example for optimal CE scenario selection, plus cost and benefits of
887 each process, or environmental impacts through LCA. In this context, DES has been used to
888 quantify flows but requires more abstract knowledge of the system, which can be resource
889 intensive. This is possibly the reason why some studies resort to describing their models
890 through hypothetical case-studies.

891   ABMS can also be coupled with external tools. Many studies considered the Theory of
892 Planned Behaviour (TPB) for modelling agents' thought process/behaviours, which
893 influenced the state transition of the ABMS. It has also been adopted to incorporate
894 regulatory behaviour and logistic constraints. Numerous studies have considered material
895 flows in terms of enterprise input-output analysis (EIOA), with metrics quantified through
896 employing stochastic- and/or indicator-based ABMS. DES has been employed, but as
897 mentioned earlier, requires extensive abstract data, which is difficult to obtain. Additionally,
898 data quality, uncertainty and selection of pertinent parameters have been considered in
899 ABMS models.

900   Thus, both SD and ABMS are flexible in modelling the complexities of system
901 thinking, by integrating various tools and techniques to quantify different aspects of circular
902 economy, which in turn leads to more informed decision-making. However, this integration
903 requires judicious thinking and case-specific challenges, which solely depends upon the
904 modeller's expert judgment.

4.4 Where we are in CE tree? – 'R'-based value retention

In the introduction, the 'R'-philosophies of CE frameworks were presented, with a more detailed elaboration available elsewhere (Jawahir and Bradley, 2016; Potting et al., 2017). **Tables 3-13** showed how the various studies considered each 'R' for each sector. Here, we discuss the aggregated view, as shown in Error! Reference source not found.. Again, it has to be noted that we are reviewing the applications of system dynamics and agent based modelling and simulation to circularity, not research on circularity per se.

It has been argued that to maximise value retention of MCPs, focus should be on the upper-part of the 'R'-based CE-tree ('R0'), instead of the lower-part ('R9'), where there are increased risks of value loss (Ellen MacArthur Foundation, 2013; Kirchherr et al., 2023). Our review demonstrates that this has not been the case to date when quantifying systems circularity: the overwhelming majority of studies reviewed here focus on recycle (R8) and recovery (R9), aside from some studies focused on reuse (R3). However, it should be noted that R2 (reduce), R3 (reuse), R8 (recycle) and R9 (recover) were the first four additions to the 'R' lexicon (Brennan et al., 2015; Yang et al., 2017) and hence have had longer to be considered within the literature. Conversely, refuse (R0) and rethink (R1) were each considered only once, despite being considered as key goals of a circular economy. However, these terms were some of the more recent additions to the 'R' lexicon (Kirchherr et al., 2017), and so some of the earlier studies may have predated their introduction. Also, much of the literature considers materials which have already entered the anthroposphere before circular economy ideas were popularised. Thus, the situation may change over the coming years as industry adopts circular design principles, incorporating durability, repairability, and recyclability.
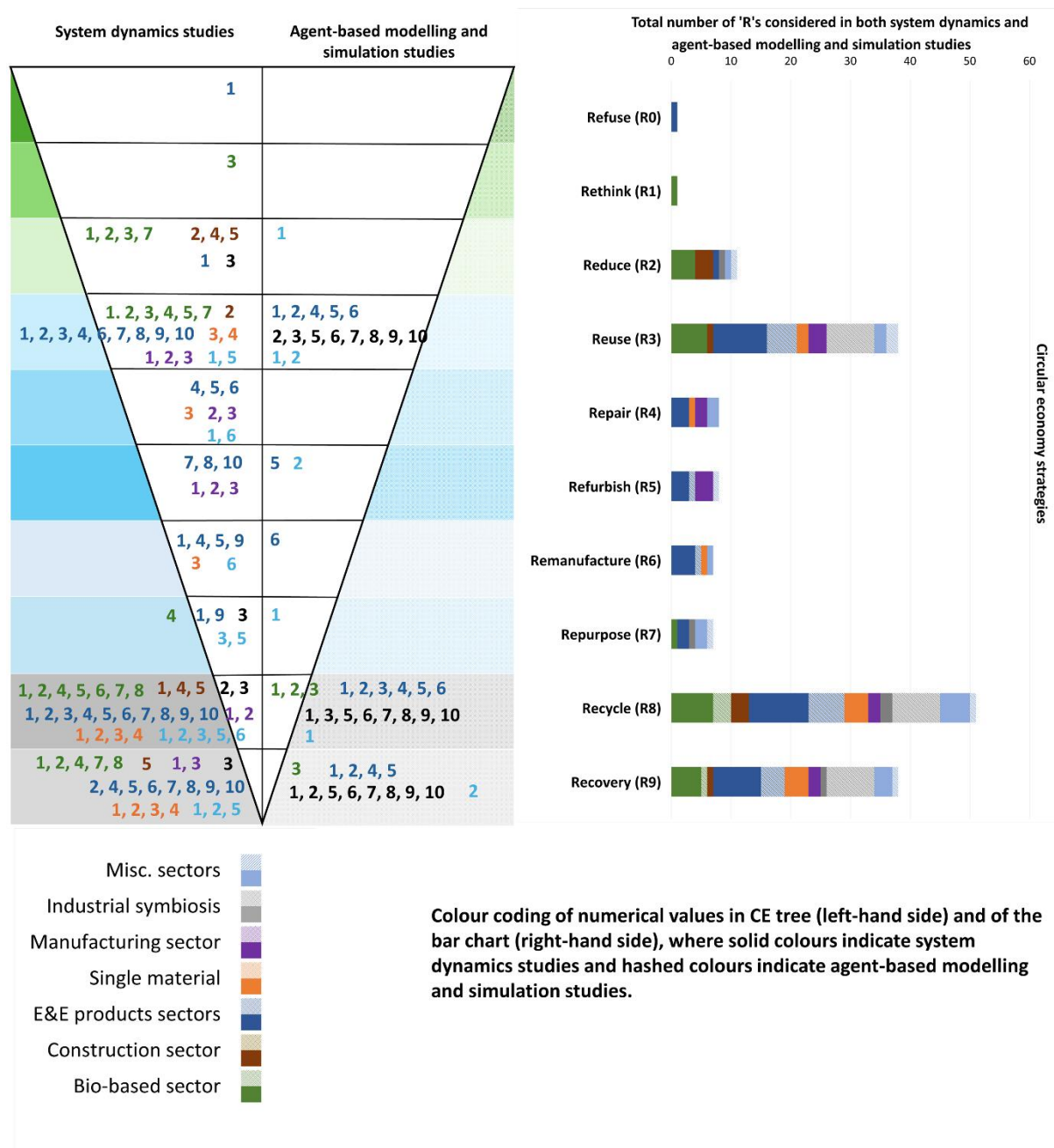
Figure 6. Prevalence of 'R'-based strategies according to each of the sectors investigated in this study. Most of the studies are focusing at the lower end of a hypothetical CE hierarchy – i.e. more extended effort cycles (i.e. recycle), where chances of value loss are perceived as being (substantially) higher.

Additional information can be gleaned by considering which R philosophies have been considered in which sector. The bio-based sector (**Section 3.1**) has focused on reduce, reuse, recycle and recovery. There has, perhaps obviously, been no consideration of repair, refurbish or remanufacture since the bio-based sector does not really concern itself with durable engineered products and these approaches are not applicable. Conversely, the products which

941 are a focus of the manufacturing and electrical and electronic products sectors feature heavily

942 from R3 (reuse) to R7 (repurpose). While there were not many studies focused on the

943 construction sector, they considered reduce (R2), reuse (R3), recycle (R8) and recovery (R9).

944   Of these studies, three of the four which considered 'R' philosophies looked at

945 demolition at either a system level (Eissa and El-adaway (2024) or at the material level

946 (Kliem et al. (2021); Mostert et al. (2022); Gandhi et al. (2024)). This reflects the status of

947 the construction industry, with global production of concrete standing at about 30 billion

948 tonnes per year (Purton, 2024), the overwhelming majority of which is used with very little

949 consideration for circularity. This is placing increasing strain on the supply of high-quality

950 aggregates (Kisku et al., 2017), with demand for sand trebling over the past two decades

951 (Gallagher and Peduzzi, 2019). Furthermore, it must be remembered that the built

952 environment typically has a long lifespan. Buildings coming to the ends of their lives now

953 were designed and built maybe 50-80 years ago, certainly at a time predating interest in

954 circularity as we perceive it today.

955   In addition, the rapid rate of modernisation and industrialisation has led to the

956 generation of substantial quantities of debris originating from construction and demolition

957 waste (CDW) (Abbas et al., 2006; Limbachiya et al., 2012). Over 700 million tonnes of

958 construction and demolition waste are produced each year (Soto-Paz et al., 2023), with

959 estimates suggesting that, in the EU at least, about 35% is end-of-life concrete (Joseph et al.,

960 2022). This is driving significant interest in the reuse of recycled concrete aggregate. This

961 does not mean that there is no interest in reuse and repurposing, just that its benefits have not

962 been quantified by SD or ABMS.

963
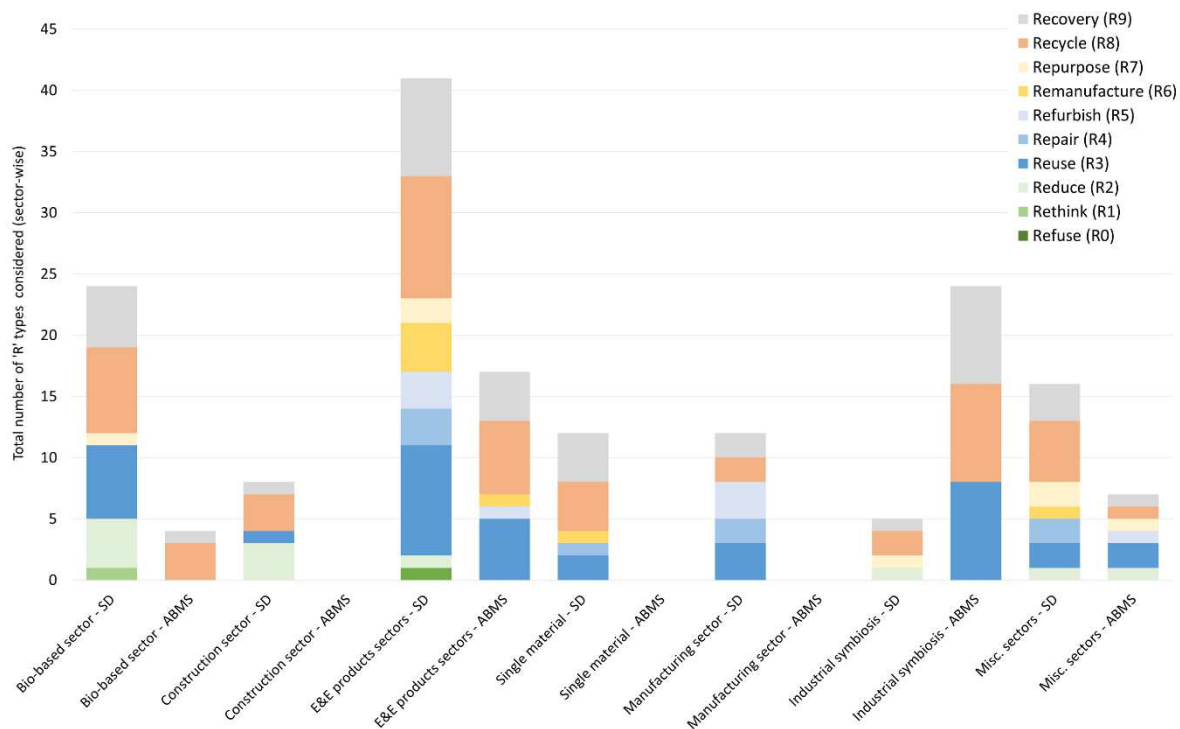
Figure 7. Total number of R-types (as stated in key) considered in studies pertaining to each sector, in adopting system dynamics (SD) or Agent-based modelling and simulation (ABMS) approaches.

968

ABMS is a recent development compared to system dynamics. This has been evident throughout this study, with there being two to three times more papers on the latter compared to the former. This is confirmed by **Figure 7** which groups the studies based on the sector. Indeed, industrial symbiosis is the only sector where studies using ABMS dominate. In this sector, the behaviour of individual agents is of key importance, hence the applicability of ABMS as an approach, with greater consideration of reuse, recycle and recovery. As seen with the studies adopting a systems dynamics approach, the focus in the bio-based sector is on recycling, reuse and recovery, with repair, refurbish and remanufacture not really applicable to the sector. In the construction sector, the focus is on reduce and recycle, reflecting perhaps greater awareness of the need to improve management of construction and demolition waste arising from existing building stocks. While there is interest in reuse, repair, refurbish and repurpose within the construction industry, it is more at the design and construction stage than at end-of-life (European Committee for Standardization, 2025). Focus in the higher-value electrical and electronics products sector is on reuse, recycle, and recovery options. Similarly, studies focussing on the manufacturing sector primarily

984 considered reuse and refurbish, again reflecting the focus of the studies being products more
985 than systems. The focus of the studies on single materials was recycle and recovery,
986 reflecting the relatively high-value materials being considered in many of the studies. Finally,
987 the miscellaneous sectors mostly focused on reuse, recycle and recovery options.
988 Additionally, from the ABMS perspective, recycle was mostly widely considered, followed
989 by reuse, and recovery. Interestingly, refuse, rethink, and repair are missing from all studies.

990

5   Future Research Directions

992 Based on the analysis and discussion, the following future research directions could be
993 suggested, mapping with the research questions (RQs) we formulated initially:

994 ***RQ1 - Need for holistic consideration for identification of leverage points in the***
995 ***circular value-chain:*** This paper started with a discussion of systems thinking and its
996 associated complexity. The purpose of systems thinking is identifying root causes of
997 challenges and solutions. In the CE context, this entails closing, slowing, or narrowing the
998 materials and energy loops. The systematic literature review showed how previous
999 literature has considered systems thinking, thereby identifying benefits of different CE
1000 related metrics, and quantifying them. Various metrics have been considered in the value-
1001 chain of the materials, components, or products (MCPs) by using system dynamics and
1002 ABMS. However, information is still lacking along the whole value-chain of MCPs from
1003 the raw material excavation to end-of-life processing, and reintroduction into the value-
1004 chain. The values (i.e., economic, environmental, social, and technical)
1005 generated/destroyed/transferred need to be considered at each process, and thereafter
1006 identifying the key leverage points (Iacovidou et al., 2017b; Millward-Hopkins et al.,
1007 2018). This will enable informed policy decisions, which will act to disrupt the current
1008 system, and in doing so reveal further leverage points, promoting further interventions,
1009 and so on in a continuous process (Boral et al., 2024). At this point, not only will the
1010 MCPs be flowing in a circular way, but so will the decisions and associated impacts. This
1011 cannot be visualised and quantified without the aid of simulation approaches.
1012 Furthermore, the review has highlighted the interdisciplinarity of circular economy
1013 research. This should be continued and encouraged for more informed circular economy
1014 decision making.

RQ2 - Modelling scale and external shocks and interventions: Interventions from governments or policy makers, and external shocks (e.g., COVID pandemic) can distort, positively or negatively simulation outputs. The impacts of interventions cannot be quantified in a deterministic way, but the stochastic and emergent properties of ABMS can model this. Also, techniques such as Poisson process (where shocks are random and independent), renewal process (where shocks occur at constant rate), and Gamma process (shocks occur at a rate that increases with time) can model shocks. Each implementation software has its own benefits and limitations, with some more suited to system dynamics and others to ABMS. The 'PySD' package in Python has the capability to model the system dynamics architecture (Martin-Martinez et al., 2022), and the 'Mesa' package in the same platform can incorporate ABMS (Masad et al., 2015). However, despite being open-sourced and freely available, to date no study has explicitly demonstrated the integration of system dynamics and ABMS within Python-based software. This integration is particularly important because, in addition to the 'PySD' and 'Mesa' packages, Python offers a wide range of AI and machine learning libraries that can be incorporated into hybrid models (e.g., for imputing missing data through various ML algorithms). Furthermore, by utilising cloud computing resources, computational time can be significantly reduced - an advantage not typically available in other platforms that support SD–ABMS integration (e.g., AnyLogic). Without such integrated, scalable implementations, holistic modelling efforts will remain largely theoretical, thereby limiting their potential for widespread industrial adoption.

RQ3 - Use of multiple simulation approaches for holistic consideration: Circular processes and associated decisions cannot be comprehensively modelled by a single simulation approach. Each approach has its advantages and drawbacks, as elaborated in detail **S.3.2** and **S.3.3**. These simulation approaches are also sufficiently flexible to be integrated with other decision-making tools, typically environmental or sustainability-focused, enabling more informed decision-making, although the static nature on non-systems tools limits inherent compatibility. The integration of different tools and techniques requires experienced systems thinkers and analysts who are also conversant with circular economy and wider sustainability assessment.

Across the systems quantification we observed a general state on data availability, uncertainty and quality. Circular economy research suffers from a lack of complete data in

1048 terms of materials, energy flows, etc (Boral and Black, 2024; Lysaght et al., 2023; Velis et

1049 al., 2021; Wang et al., 2024, 2022). Moving across scales, from 'micro' level analysis to

1050 'meso' or 'macro' level, another challenge is data aggregation, assuming data is available.

1051 Then, when system boundaries expand, modelling data uncertainty and quality are further

1052 challenges. Although fuzzy, and Bayesian MFA are options to account for data uncertainty,

1053 they cannot handle the system dynamicity, and thus their application to holistic circular

1054 economy systems is still lacking. This can only be solved through open data and software

1055 platforms capable of multiple modelling approaches.

1056 Although BS ISO 59004:2024 has recently proposed some overarching aspects of CE

1057 practice, along with how different stakeholders can benefit from that (The British Standards

1058 Institution, 2024a), it omits details of modelling complex CE systems, and thereby their

1059 quantification. Likewise, while the standard provides a list of CE metrics and states how

1060 value metrics are complex, the list of metrics inevitably cannot be comprehensive, and the

1061 standard does not consider how the metrics may change through a system's inherent

1062 complexity. Our study is the first to highlight how different circularity metrics have been

1063 quantified using system dynamics and ABMS approaches. Overall, our PRISMA-ScR review

1064 provides insights into the strengths and limitations of these approaches, paving the way for

1065 further research in CE systems modelling.

1066 **6   Conclusions**

1067 Systems thinking in the CE context refers to a holistic, interconnected approach that

1068 recognises economies, industries, and societies as complex systems where all parts interact

1069 and influence one another. The application of systems thinking to circularity is not a new

1070 concept, but its application to quantify aspects of circularity is still at a nascent stage.

1071 Furthermore, systems thinking is a theoretical paradigm, but it remains unclear how it can be

1072 adopted to capture the complexities associated with CE system, and thereby quantify

1073 different metrics without them existing in isolation, but as interconnected entities. This

1074 review, based on a PRISMA-ScR framework, synthesised studies that used system dynamics

1075 and ABMS to capture CE complexities and demonstrate how abstract systems concepts can

1076 be operationalised. System dynamics provides a top-down, aggregated view through causal

1077 loops, stocks and flows, and temporal dynamics, while ABMS enables a bottom-up

1078 representation of heterogeneity, adaptiveness, emergence, and spatio-temporal interactions,

1079 which are particularly relevant to practical CE modelling. This latter approach is more recent

1080 and so is still developing. Consequently, the combination of system dynamics and ABMS has

1081 not yet been applied in a circular economy context; similarly limited are attempts to

1082 concurrently consider metrics from separate circularity domains of value – especially

1083 incorporating social aspects – despite the strong potential for enhanced circularity

1084 quantification such an approach could bring. Further combining system-level quantification

1085 with other sustainability-focused decision-support tools (well established but currently

1086 mainly static) could enable more informed decision-support on advancing circular economy

1087 theory and practice by industry and policymakers.

1088

CRediT Author Statement

Soumava Boral: Conceptualisation, Methodology, Writing – Original draft preparation, Formal analysis, Data Curation, Visualization; **Leon Black:** Conceptualisation, Writing – Review and Editing, Visualisation, Supervision, Funding acquisition; **Costas Velis:** Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Project administration, Funding acquisition.

Data Availability Statement

All data associated with this study are available in the article and in the **Supplementary Material (SM)**.

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