Critical literature review of quantitative sustainability assessment methods for the circular economy

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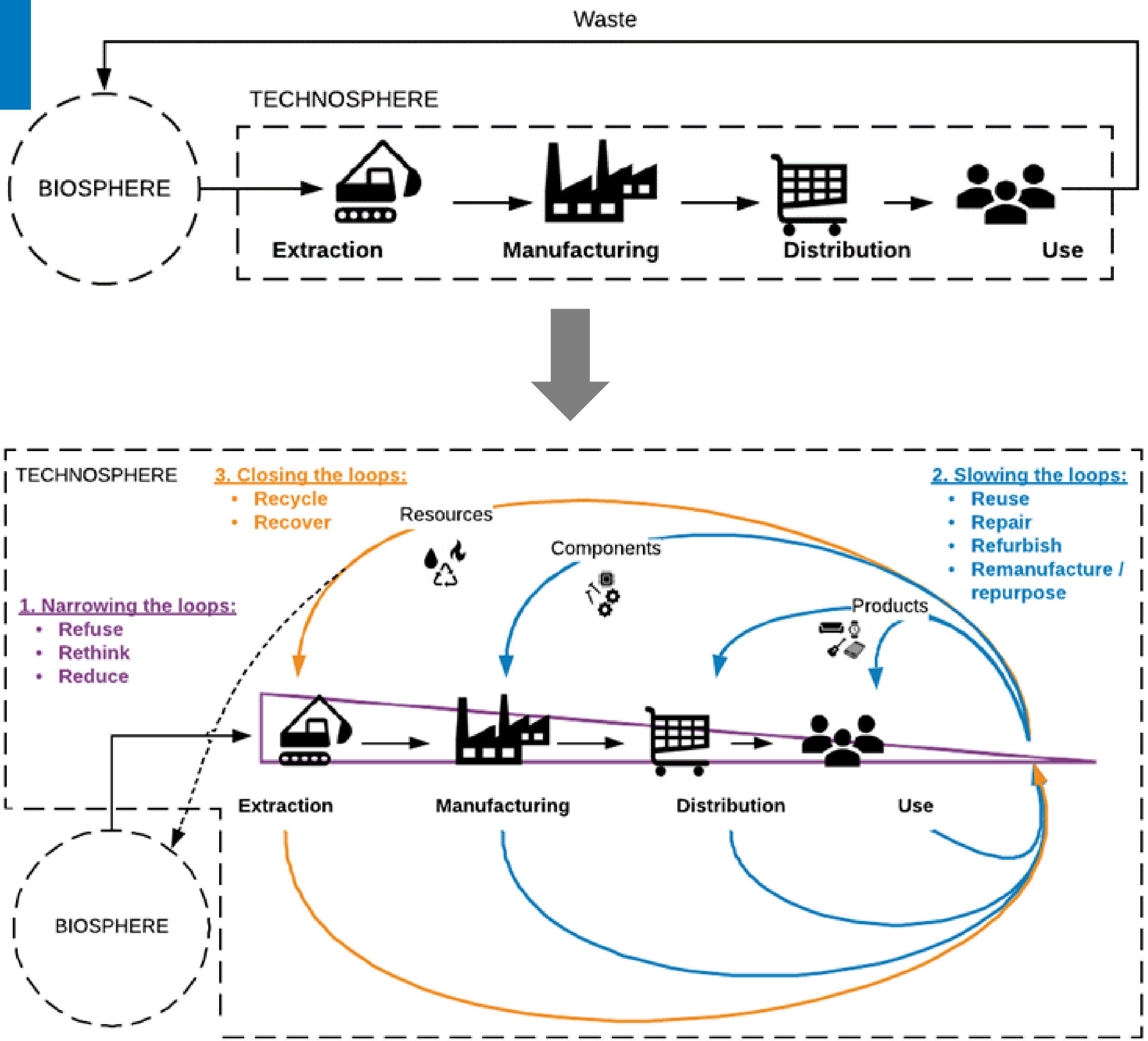
Plan

- Context and motivations of the literature review
- Review approach and critical analysis framework
- Review of assessment methods and implications
- Conclusion

Context and motivations of the literature review

- **Problem:** Between 2015 and 2060, demand for raw materials is expected to increase (e.g., 3000% for PV) (Sovacool, 2020)

- **A solution?** The circular economy (CE) spurs material efficiency e.g., through reusing/recycling products
  - In 2050 projected PV waste = 7.5-10 million tonnes
  - CE could capture value from PV waste, lowering demand for raw materials



From a linear to a circular economy

Context and motivations of the literature review

- Many CE literature reviews, for instance on:
  - CE definitions (e.g., Kirchherr et al., 2017; Teigiserova et al., 2020; Farooque et al., 2019)
  - Metrics (e.g., Parchomenko et al., 2019; Moraga et al., 2019; Saidani et al., 2019)
  - Assessment methods (Sassanelli et al., 2019; Merli et al., 2018; Roos Lindgreen et al., 2020)

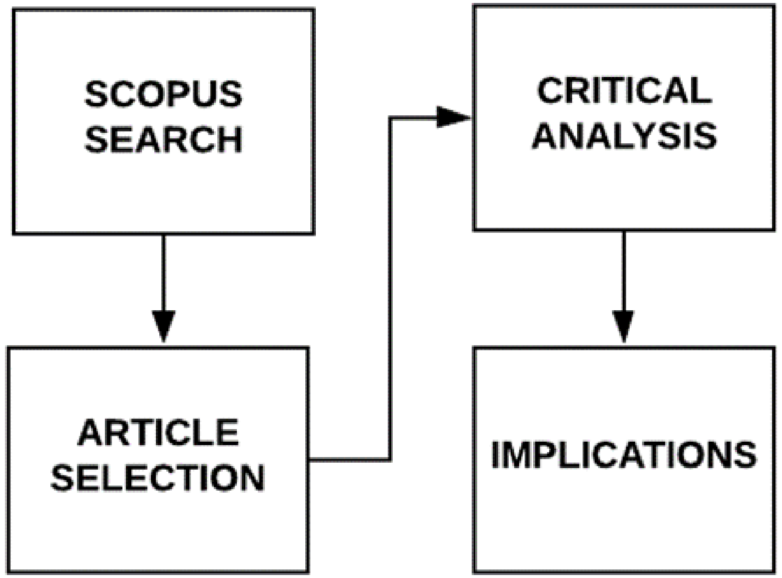
- Limitations of current reviews:
  - No guidance for the selection of methods underpinning metrics & tools
  - No information on methods' characteristics (e.g., temporal and geographical scopes)

  → Need for guidance about which quantitative sustainability assessment method (or combination of methods) are best suited to assess which specific CE-related research questions

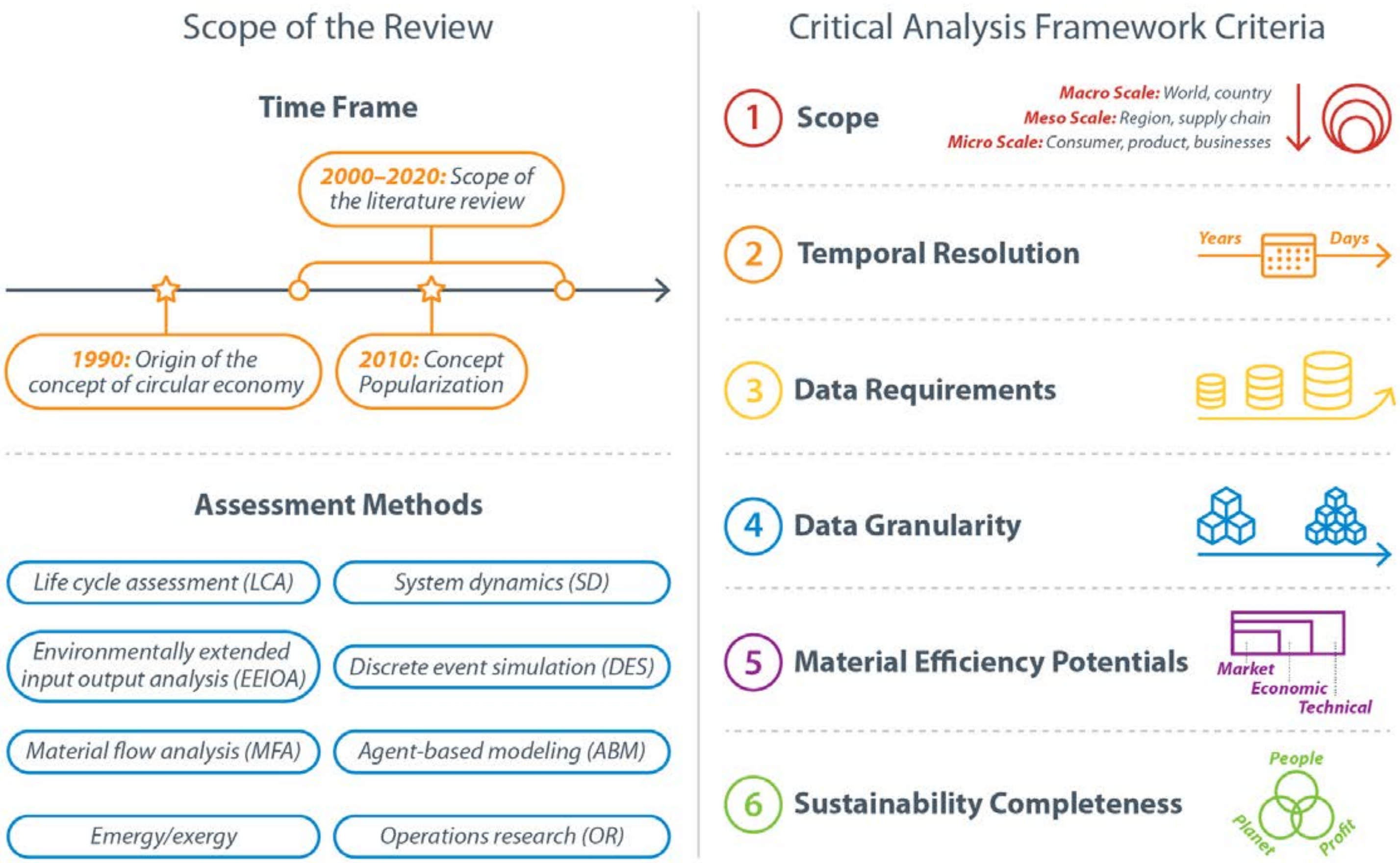
Review approach and critical analysis framework

- Literature review:
  - **Goal:** provide guidance on what type of information different quantitative sustainability assessment methods can yield for circularity assessments
  - Scopus search: keyword combinations of "circular economy" and 8 assessment methods, 824 articles found → 92 articles selected based on publication year and journal

- Critical analysis based on six criteria:
  - Scope
  - Temporal resolution
  - Data requirements
  - Data granularity
  - Material efficiency potentials
  - Sustainability completeness



Review approach and critical analysis framework



Critical analysis framework rationale: CE needs to be implemented at different scale (Merli et al., 2018), and occurs with time (Ghisellini & Ulgiati, 2020). Different material efficiency potentials need to be differentiated as CE implies adoption of new production and consumption behaviors (Moraga et al., 2019).

Review of assessment methods and implications

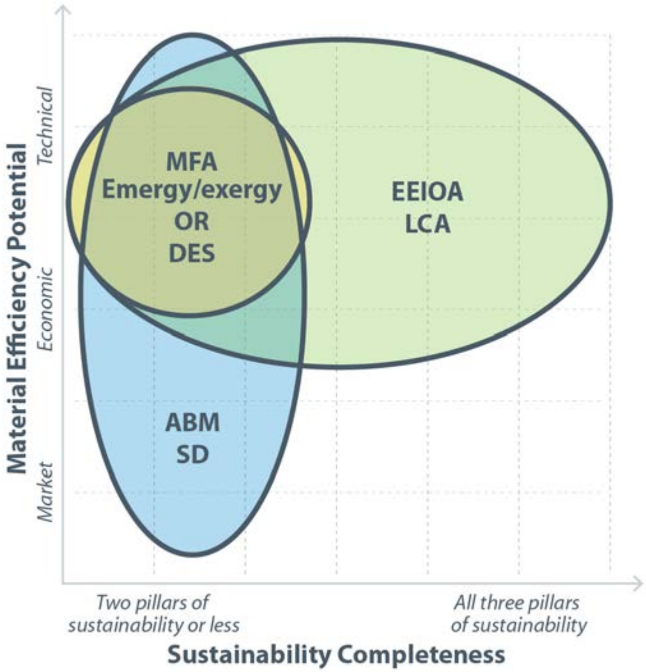
- Methods reviewed are from two broad fields:
  - Industrial ecology:
    - Life Cycle Assessment (LCA) = Evaluates environmental impact across a product life cycle
    - Environmental Extended Input Output Analysis (EEIOA) = Quantifies environmental impacts stemming from economic activities
    - Material Flow Analysis (MFA) = Tracks flows of a material or substance in a system (e.g., a city)
    - Emergy and Exergy (Em/Ex) = Track flows of energy in a system
  - Complex systems science:
    - System Dynamics (SD) = Models complex systems from the top-down, accounting for feedback mechanisms and nonlinear behaviors
    - Agent-Based modeling (ABM) = Models complex systems from the bottom-up using agents which have their own behaviors and interact with each other and their environment
    - Discrete event simulation (DES) = Models complex systems from the bottom-up using deterministic or stochastic events
    - Operations Research (OR) = Seeks the optimal solution to a problem

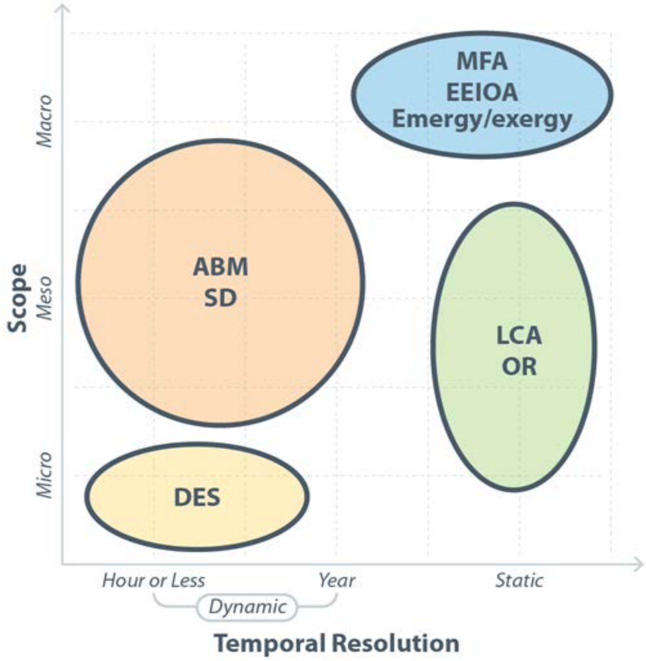
Review of assessment methods and implications

- Methods from industrial ecology:
  - Usually do not account for temporal aspects
  - Often cover a wider range of sustainability attributes
  - Are not adapted to represent social dynamics

- Methods from complex systems science:
  - Are inherently dynamic
  - Often focus on just one or a few sustainability attributes Can represent social dynamics and therefore the market potential of material efficiency

- Both fields have methods spanning different scope



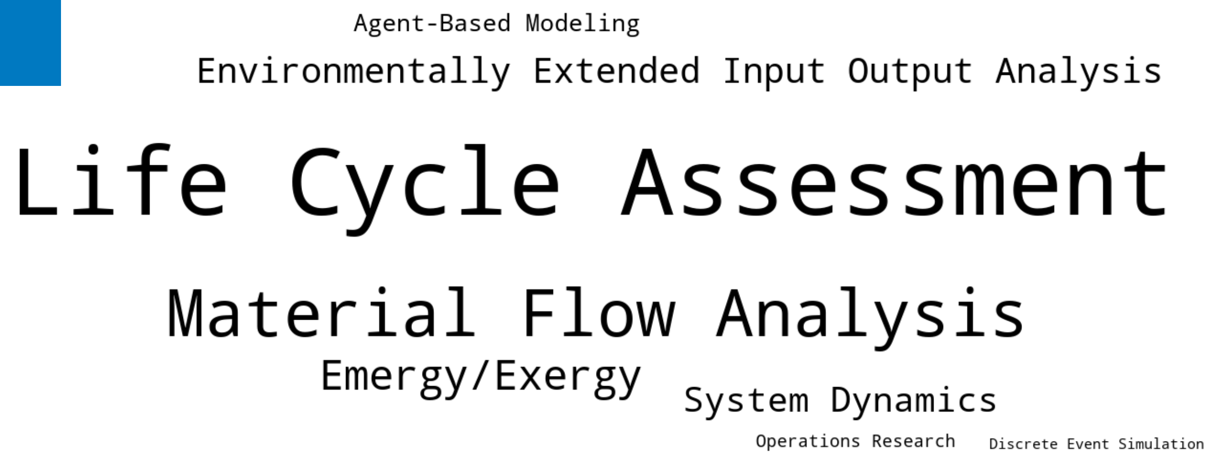


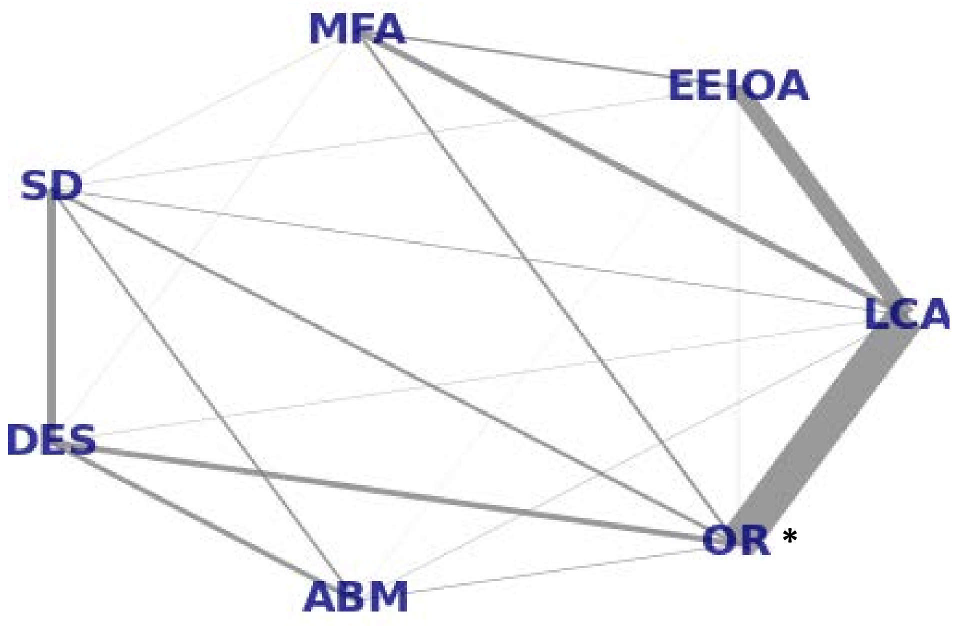
Review of assessment methods and implications

- Methods from industrial ecology have been mostly used for circularity assessment (see word cloud)

- Combining methods from industrial ecology and complex systems science could alleviate some of their shortcomings

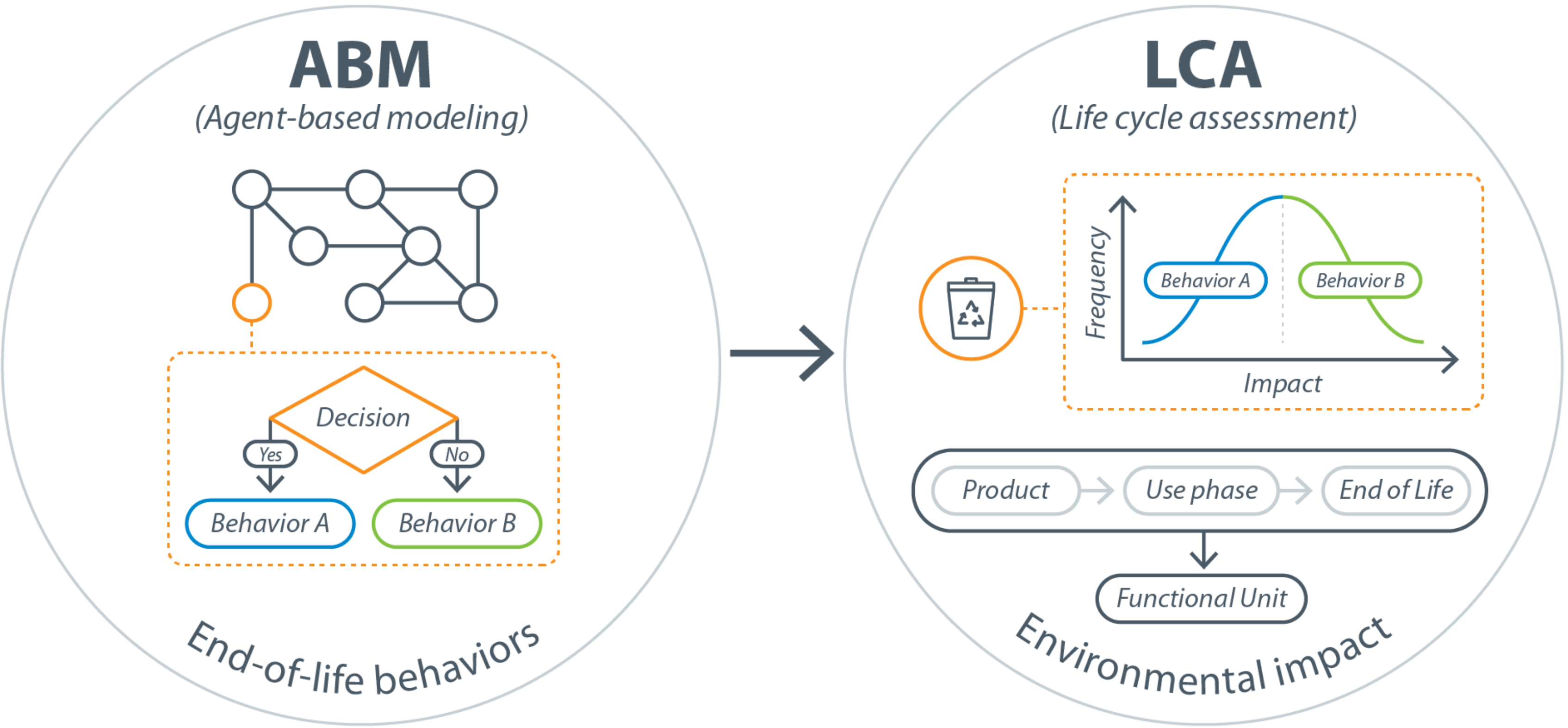
- Methods from both fields have been mostly combined within their own field → opportunities to extend their scope of analysis when applied to CE assessments





*OR is a broad field that includes several approaches that have been combined with LCA

Review approach and critical analysis framework



Example of the use of combined ABM and LCA in the context of the circular economy: ABM enable representing the decisions of the various CE actors (e.g., consumers, manufactures, recyclers) while LCA evaluates the environmental impacts stemming from those decisions. A typical decisions for consumers would be, for instance, to recycle a product or dump it. ABM provides better scenario modeling capacity that might lead to more realistic LCA results.

Review of assessment methods and implications

- Summary Table of the strengths and weaknesses of each method for circularity assessment

- Examples:

Method	Research Question	Strengths	Relevance to CE *(numbers 1, 2… correspond to related strengths)*	Weaknesses	Potential solution *(letters A, B… correspond to related weaknesses)*	Possible output metric(s)
Industrial ecology						
LCA	What are the environmental impacts related to a product or system?	**1.** Models technological processes and their various impacts on the environment **2.** Systemic view **3.** Also accounts for socio-economic impacts	**(1)** Able to assess the sustainability of the CE **(2,3)** Avoidance of impact displacements	**A.** Data intensive **B.** Does not model market potential **C.** Static	**(A)** Sensitivity analysis **(B,C)** Combination with other methods (e.g., EEIOA, ABM)	Raw Material Consumption (RMC), Environmental Interventions (LCI), Environmental Impact (LCIA)
ABM	What are the interactions among a systems' individual parts and how do they drive its overall behavior?	**1.** Models heterogeneity (system structure is not prescribed) **2.** Represents social interactions **3.** Models decisions that are not necessarily rational **4.** Information on parts and whole of the system **5.** Includes feedback loops **6.** Dynamic	**(1)** Explore relationships between various actors in the CE **(2)** Requires industrial symbiosis and social change **(3)** Able to model market potential **(4)** Able to model CE transitions at various scales **(5)** Industrial symbiosis captures feedback loops, which are important to industrial symbiosis **(6)** Able to model the CE over time	**A.** Data intensive **B.** Difficult to validate **C.** Difficult to generalize	**(A,B)** Calibration and sensitivity analysis **(B)** Simple, general model with further refinements	End-of-life rates, Raw Material Consumption (RMC), Waste ratio, Waste and recycling per capita, Decoupling factor, Value added at factor cost

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Industrial ecology						
LCA	What are the environmental impacts related to a product or system?	**1.** Models technological processes and their various impacts on the environment **2.** Systemic view **3.** Also accounts for socio-economic impacts	**(1)** Able to assess the sustainability of the CE **(2,3)** Avoidance of impact displacements	**A.** Data intensive **B.** Does not model market potential **C.** Static	**(A)** Sensitivity analysis **(B,C)** Combination with other methods (e.g., EEIOA, ABM)	Raw Material Consumption (RMC), Environmental Interventions (LCI), Environmental Impact (LCIA)
EEIOA	What are the environmental impacts related to an economic system?	**1.** Models economic sectors and their various impacts on the environment **2.** Systemic view **3.** Can account for socio-economic impacts **4.** Incorporates system boundary beyond a single process	**(1)** Able to assess the sustainability of the CE **(2)** Avoidance of impact displacements **(3)** Looks at CE as a whole	**A.** Fewer environmental interventions accounted for than in LCA **B.** Does not model market potential **C.** Static	**(A)** Use of LCA databases to complement environmental assessment **(B,C)** Combination with other methods (e.g., ABM, SD)	Raw Material Consumption (RMC), Material Footprint (MF), Circularity gap index (CGI), Waste ratio, Environmental Interventions (LCI), Environmental Impact (LCIA)
MFA and emergy/ exergy	What are the material (or energy) flows and stocks related to a system?	**1.** Accounts for stocks **2.** Systemic view	**(1)** Assesses material use **(2)** Analyzes trade-offs	**A.** Fewer environmental interventions accounted for than in LCA **B.** Lack of details on system processes **C.** Does not model market potential **D.** Static	**(A,B)** Use of LCA databases to complement environmental assessment **(C,D)** Combination with other methods (e.g., SD)	Direct Material Input (DMI), Total Material Requirement (TMR), Total Domestic Output (TDO), Domestic Material Consumption (DMC), Processed Material (PM), Raw Material Consumption (RMC), Material Footprint (MF), Net Addition to Stock (NAS)…
Complex systems science						
SD	How do underlying system structures influence the behavior of complex dynamic systems (e.g., systems with interdependence, mutual interaction, information feedback, and circular causality)?	**1.** Models decisions that are not necessarily rational **2.** Represents market dynamics and social system behavior **3.** Information on parts and whole of the system **4.** Includes feedback loops **5.** Dynamic	**(1)** Able to model market potential **(2)** Able to explore relationships between system structure and social and market dynamics **(3)** Able to model CE transitions at various scales **(4)** Captures feedback loops, which are important to industrial symbiosis **(5)** Able to model the CE over time	**A.** Does not always include details on system processes **B.** Can be more data intensive **C.** Can be difficult to generalize	**(A)** Combination with other methods (e.g., ABM, DES) **(B)** Calibration and sensitivity analysis **(C)** Simple, general model with further refinements	End-of-life rates, Net Addition to Stock (NAS), Raw Material Consumption (RMC), Waste ratio, Waste and recycling per capita, Decoupling factor, Value added at factor cost
DES	What is the sequence of (eventually stochastic) events that triggers the dynamics of a system?	**1.** Detailed description of processes **2.** Represents randomness of events **3.** Dynamic	**(1)** Help rethink processes within circular strategies) **(2,3)** Able to model the CE over time	**A.** Data intensive **B.** Focus on micro-scale **C.** Does not include feedback loops	**(A)** Calibration and sensitivity analysis **(B,C)** Combination with other methods (e.g., SD)	Raw Material Consumption (RMC), Waste ratio, Decoupling factor, Value added at factor cost
ABM	What are the interactions among a systems' individual parts and how do they drive its overall behavior?	**1.** Models heterogeneity (system structure is not prescribed) **2.** Represents social interactions **3.** Models decisions that are not necessarily rational **4.** Information on parts and whole of the system **5.** Includes feedback loops **6.** Dynamic	**(1)** Explore relationships between various actors in the CE **(2)** Requires industrial symbiosis and social change **(3)** Able to model market potential **(4)** Able to model CE transitions at various scales **(5)** Industrial symbiosis captures feedback loops, which are important to industrial symbiosis **(6)** Able to model the CE over time	**A.** Data intensive **B.** Difficult to validate **C.** Difficult to generalize	**(A,B)** Calibration and sensitivity analysis **(B)** Simple, general model with further refinements	End-of-life rates, Raw Material Consumption (RMC), Waste ratio, Waste and recycling per capita, Decoupling factor, Value added at factor cost
OR	What is the best solution for a decision-making problem?	**1.** Aims at finding the optimal solution **2.** Suitable for representing cooperation	**(1)** Identification of the best strategy **(2)** Requires industrial symbiosis	**A.** Computationally intensive **B.** Solution may not exist or there may be an infinity of solutions **C.** Static	**(A)** Simplify model **(B)** Use of heuristics **(C)** Combination with other methods (ABM, SD…)	End-of-life (recycling, reusing…) rates, Raw Material Consumption (RMC), Waste ratio, Decoupling factor, Value added at factor cost

Conclusion

- Methods from two broad fields emerge from the review:
  - Industrial ecology methods have been mainly applied for circularity assessment.
  - Complex systems science methods can model the adoption of the new production and consumption behaviors that CE entails, therefore, representing the market material efficiency potential of a CE strategy in addition to its techno-economic potentials.

- Complex systems science methods provide better scenario modeling capacity that might lead to more realistic sustainability assessment results.

- Methods could complement each other. For instance, the system could be simulated with SD or ABM, while LCA or EEIOA (depending on the scope of the analysis) could provide information on environmental impacts of envisioned circular economy strategies. Lastly, multi-criteria decision analysis could help choose the best alternatives.

Thank you!

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