Advancing LCA by Integrating Socio-Technical Complexity through Agent-Based Modelling

International Industrial Ecology Day - 2025

Life Cycle Thinking for Complex Systems Initiative
[complexity.lca@gmail.com]
[complexitylca.github.io]

November 21st , 2025

Today's agenda

Moderator:
Gustavo Larrea-Gallegos
Luxembourg Institute of Science and Technology (LIST), Luxembourg

1. **About the initiative**
   Agnese Fuortes
   National Institute for Public Health and the Environment (RIVM), The Netherlands

2. **Introduction of Complexity**
   Jonathan Cohen
   Chalmers University of Technology, Sweden

3. **Contribution of Agent-Based Modelling in Different Advancement of LCA**
   Kasper Lange
   Amsterdam University of Applied Sciences, The Netherlands

4. **Paradigm Shifts in IE Research through Integrating Agent-Based Modelling**
   Ryu Koide
   National Institute for Environmental Studies (NIES), Japan

Introducing Life Cycle Thinking for Complex Systems Initiative

Agnese Fuortes
National Institute for Public Health and the Environment (RIVM), The Netherlands

Life-Cycle Thinking for Complex Systems Initiative

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- **Life-Cycle thinking for sustainability**
  (e.g., LCA, Input-Output, etc)

- **Complexity-driven methodologies**
  (e.g., ABM, network analysis, simulation methods)

- **Complex Systems**
  (e.g., socio-technical systems, techno-ecological networks)

Life-Cycle Thinking for Complex Systems Initiative

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- Promote the use of complexity-oriented methods in combination with life-cycle thinking approaches.

> provide a platform

> beyond domains

Life-Cycle Thinking for Complex Systems Initiative

- **Newsletter:** complexity-lca@gaggle.email
    - **Stay informed**

      -> Future activities
    - **Share**

      -> Events
      -> Job opportunities

Life-Cycle Thinking for Complex Systems Initiative

- Check out the website: complexitylca.github.io

Complexity-LCA documentation

Search Ctrl + K

About the initiative

Events

Recommended literature

Recommended literature and resources

Agent-based modeling and life cycle thinking: key review and methodological papers

- Micolier, A., Loubet, P., Taillandier, F., Sonnemann, G., 2019. To what extent can agent-based modelling enhance a life cycle assessment? Answers based on a literature review. Journal of Cleaner Production 239, 118123. https://doi.org/10.1016/j.jclepro.2019.118123
- Hicks, A., 2022. Seeing the people in LCA: Agent based models as one possibility. Resources, Conservation & Recycling Advances 15, 200091. https://doi.org/10.1016/j.rcradv.2022.200091
- Davis, C., Nikolić, I., Dijkema, G.P.J., 2009. Integration of Life Cycle Assessment Into Agent-Based Modeling: Toward Informed Decisions on Evolving Infrastructure Systems. J of Industrial Ecology 13, 306–325. https://doi.org/10.1111/j.1530-9290.2009.00122.x
- Larrea-Gallegos, G., Marvuglia, A., Navarrete Gutiérrez, T., Benetto, E., 2024. A computational framework for modeling socio-technical agents in the life-cycle sustainability assessment of supply networks. Sustainable Production and Consumption 46, 641–654. https://doi.org/10.1016/j.spc.2024.03.008
- Dijkema, G.P.J., Xu, M., Derrible, S., Lifset, R., 2015. Complexity in Industrial Ecology: Models, Analysis, and Actions: Complexity in Industrial Ecology. Journal of Industrial Ecology 19, 189–194.

Contents

Agent-based modeling and life cycle thinking: key review and methodological papers

Agent-based modeling: textbooks and guidelines

Agent-based modeling: software and packages

Agent-based modeling: online lectures and summer schools

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- July 2024 — Launching webinar
- Nov 2024 — Industrial Ecology day
- Aug 2025 — Social Simulation Conference
- In progress — Co-authoring a forum paper
- Today — Industrial Ecology day
- Special sessions at conference(s)
- Co-developing platforms/methods
- Online coffee breaks/sessions

Follow-up working session

For those interested in contributing to the initiative
5th December 10:00 AM Central European Time

Zooom URL will be emailed later to your registered email address to this IE day event.

Please email us (complexity.lca@gmail.com) if you are interested in but cannot attend the follow-up session!

Contact us: [complexity.lca@gmail.com]

Visit the website: [complexitylca.github.io]

Why do we need complexity science methods in Industrial Ecology?

Jonathan Cohen
Chalmers University of Technology, Sweden

Industrial ecology examines the behavior of complex socio-technical systems embedded within environmental and institutional contexts. Recognizing system complexity is critical, as sustainability outcomes emerge from the interactions between technologies, human behavior, resource flows, and regulatory frameworks.

Complex system

Complex Adaptive System (CAS)

Socio-technical system (STS)

Environmental
institutional
production and
consumption systems

What topics do you work on in the context of sustainability?

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Facing wicked problems (3/10)

Dilemmas in a general theory of planning (Rittel & Webber, 1973)

1. They do not have a definitive formulation.
2. They do not have a “stopping rule.”
3. They cannot be studied through trial and error: “every trial counts”.

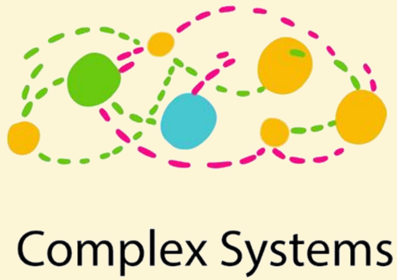
One-Shot operations.

Heterogeneous network

Complexity arises because **diverse and distributed actors interact across scales and goals**, producing emergent outcomes.

In Industrial Ecology:

- Multiple actors with different goals and perspectives
- Interactions across different system levels (e.g., firm ↔ region ↔ global supply chain)
- Conflicting or overlapping objectives (economic, environmental, social)
- Decentralized or self-organized decision-making



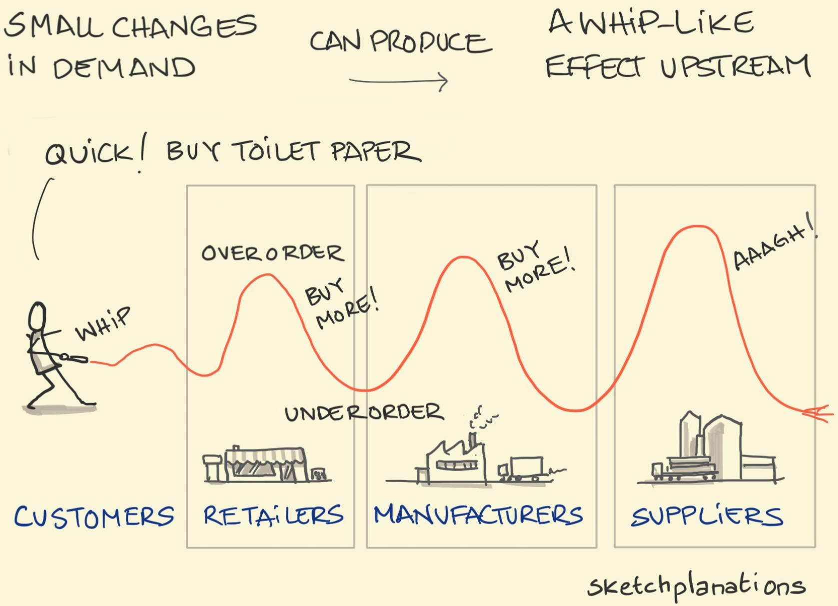
Nonlinear dynamics

Disproportional causation/Sensitivity to initial conditions

In Industrial Ecology:

- Efficiency improvements may lead to **rebound effects.**
- Scaling up a circular solution does not yield proportionally lower impacts.
- Policy incentives may produce unintended side effects.

Driven by: feedback loops and interconnected processes.



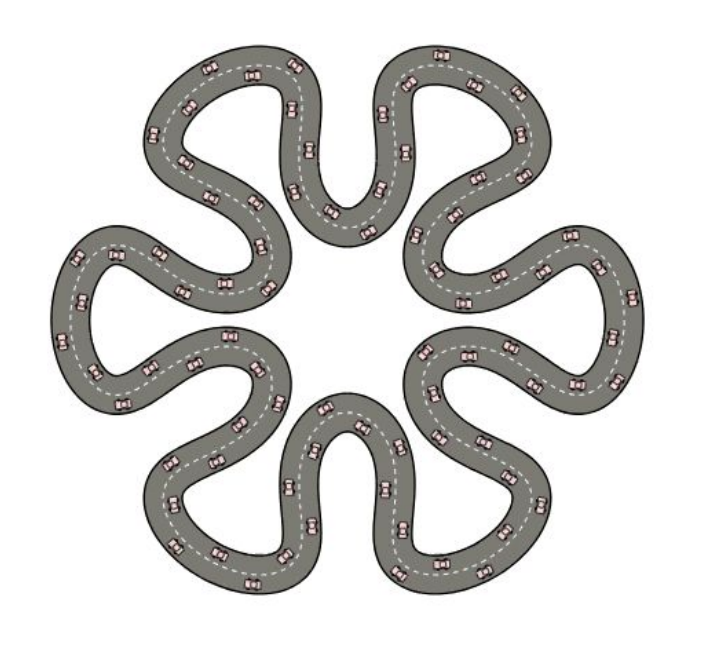
Emergence

Macro-level emergent patterns can arise from micro-level decision-making processes

In Industrial Ecology:

- Industrial symbiosis networks forming spontaneously.
- New circular economy business models emerging from local collaboration.
- Aggregate environmental impacts emerging from many decentralized actions.

Driven by: interactions, adaptation, and diversity of agents.



The emergence of phantom traffic jams based on Complexity Explorable: " Berlin 8:00 a.m. - How speed variation may trigger persistent traffic congestion"

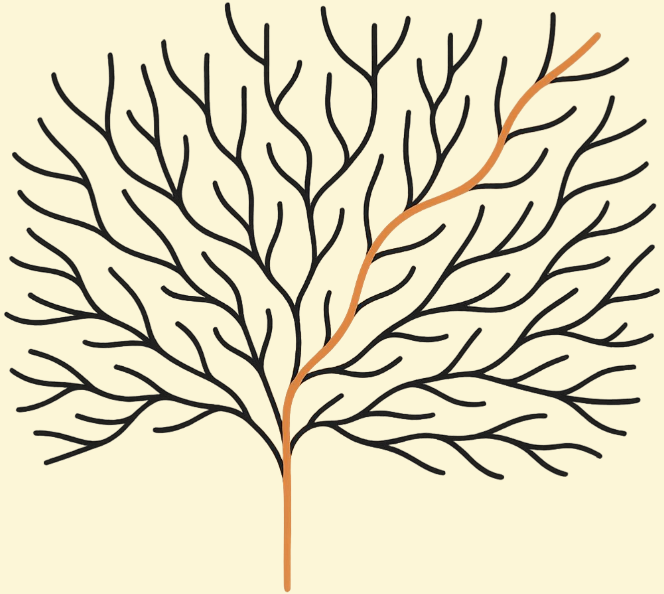
Path dependence

Past decisions constrain present and future options.

In Industrial Ecology:

- Lock-in to carbon-intensive infrastructures.
- Historical policy or investment patterns shaping future transitions.
- Early adopters can make a technology dominant.

Driven by: reinforcing feedbacks.

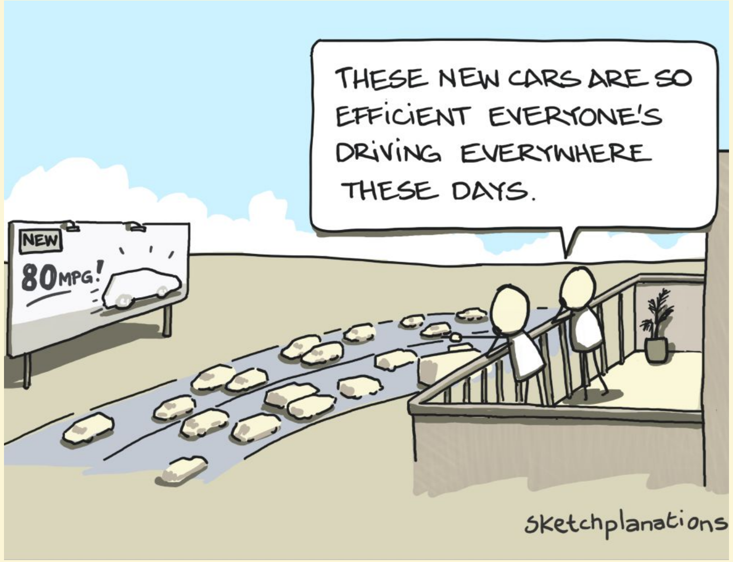


Adaptation

Actors within the system adjust their strategies, technologies, or behaviors.

In Industrial Ecology:

- Firms responding to environmental regulation or market shifts.
- Consumers adapting to new product designs or pricing.
- Supply chains reorganizing after disruptions.



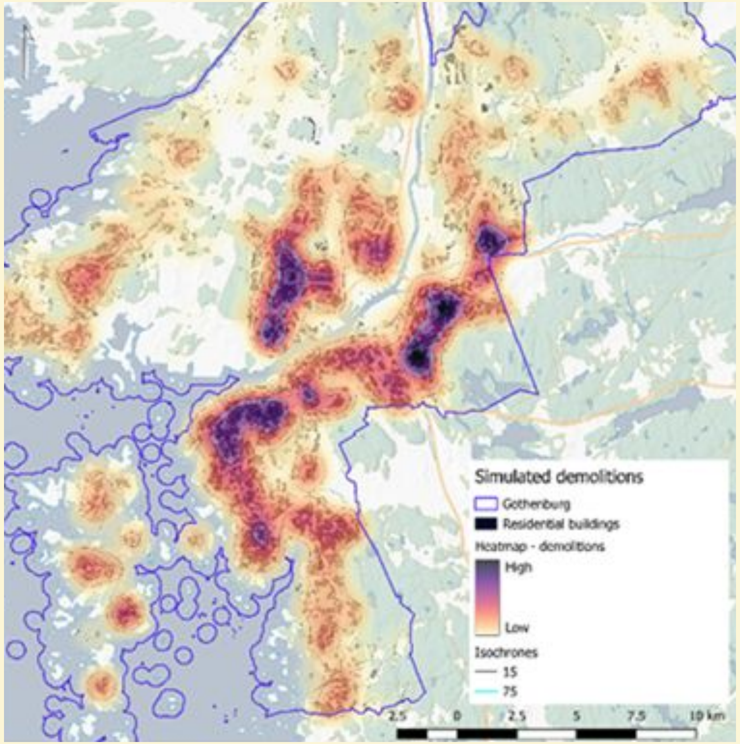
Driven by: feedback from performance, policy, or environment.

Spatial

Agents and objects occur in space and 'closer things are related to each other'

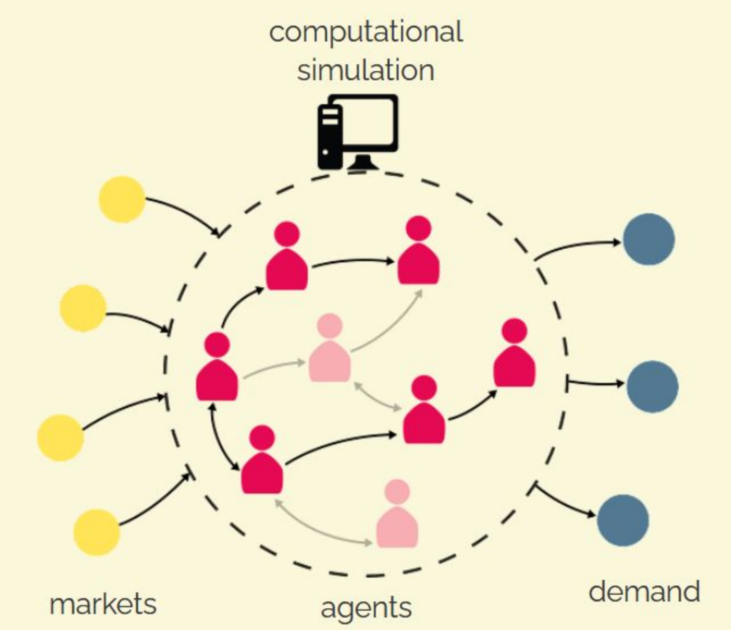
In Industrial Ecology:

- Trust and knowledge spillover
- Access and proximity to resources and opportunities
- Economic activity clusters at different scales

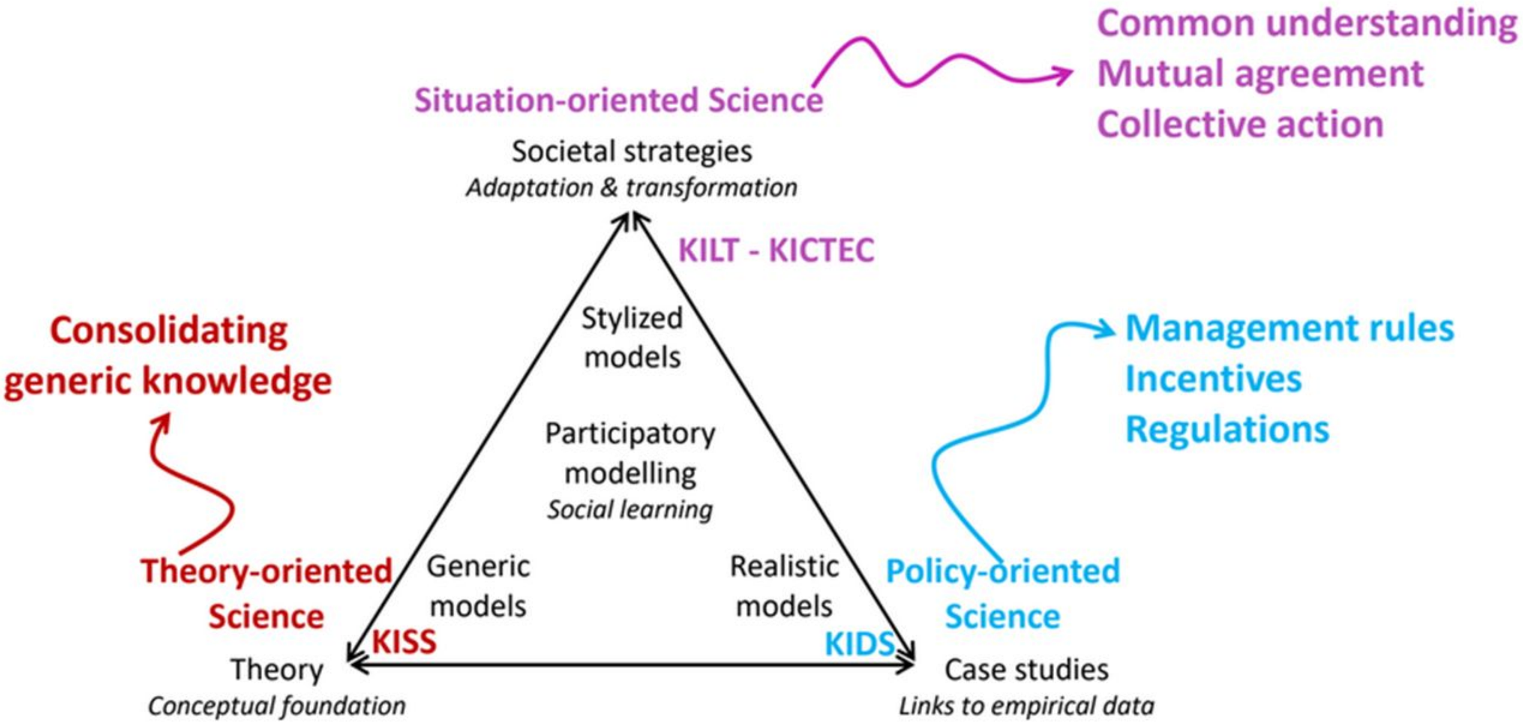


Driven by: feedback from performance, policy, or environment.

Agent Based Modelling (ABM) is a popular paradigm that allows to study complex systems



Moving towards multi disciplines



Le Page and Perrrotton, 2017

What kind of complexity do you face in your projects?

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Contribution of agent-based modelling in advancement of LCA

Kasper Lange
Amsterdam University of Applied Sciences, The Netherlands

Typical flavours of LCA

Defining aspects of LCI modelling	**LCA flavour**	**LCI aims at**
Dynamicity	Dynamic LCA	modelling effects over time
Temporality	Prospective LCA	looking forward instead of evaluating established systems
Scale	Territorial LCA	studying a larger scale target system (aggregated territorial units instead of products or organisations).
Causality	Consequential LCA	endogenizing cause-and-effect relationships of decision-making and policies on impact

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

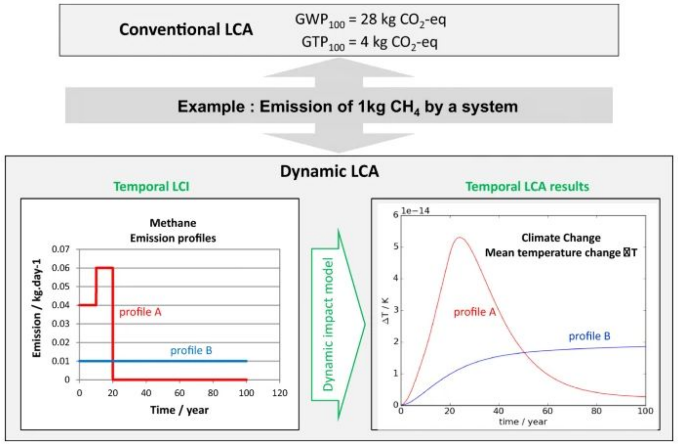
Dynamicity and temporality

Dynamicity *refers to how a system modelled in LCA changes over time*

Temporality *refers to the point in time that the LCI model represents or aims to represent, with respect to the intended use of LCA results*

- Most LCA studies use retrospective models, due to data availability.
- Forward-looking approaches have been developed to provide decision-making support.

<u>Incorporating dynamicity and temporality requires methods beyond mainstream analytical techniques, e.g. scenario modelling.</u>



Importance of time dependence in the calculation of the climate change impact of 1 kg methane emission (from Shimako et al. 2018)

Figure: Pigné et al. (2020)

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Dynamicity and temporality and Agent Based LCA

AB-LCA can yield dynamic models in forward-looking LCA.

Existing AB-LCA studies already include dynamicity and temporality:

- 58% future oriented
- 21% current context
- 21% no temporal definition

<u>Studies aim to align the simulation duration and granularity with the goal and scope of the LCA</u>

However, granularity mostly depends on data availability over time

Source: Carrey et al. (in press)

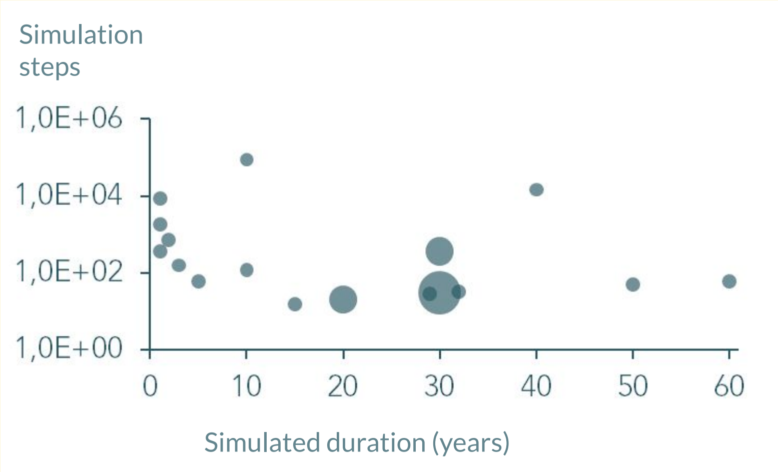


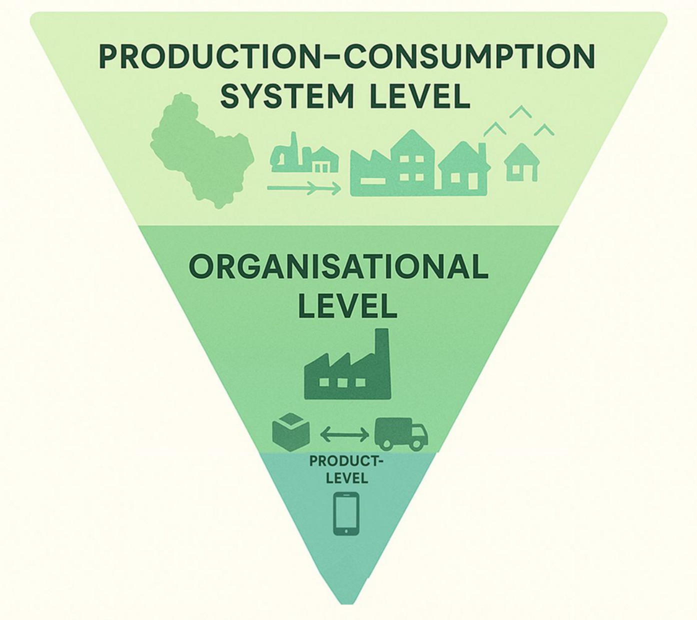
Figure: Carrey et al. (in press)

Scale

Scale *refers to the extent of the target system at which LCA is conducted*

- Product-level
- Organisational level
    - Products, services and activities
    - Also across operations and value chain
- Production-consumption system level within a defined territory

Territorial LCA often shows how decisions at the territorial level could affect other regions. <u>However, the interplay between decisions at various levels remains understudied.</u>



Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

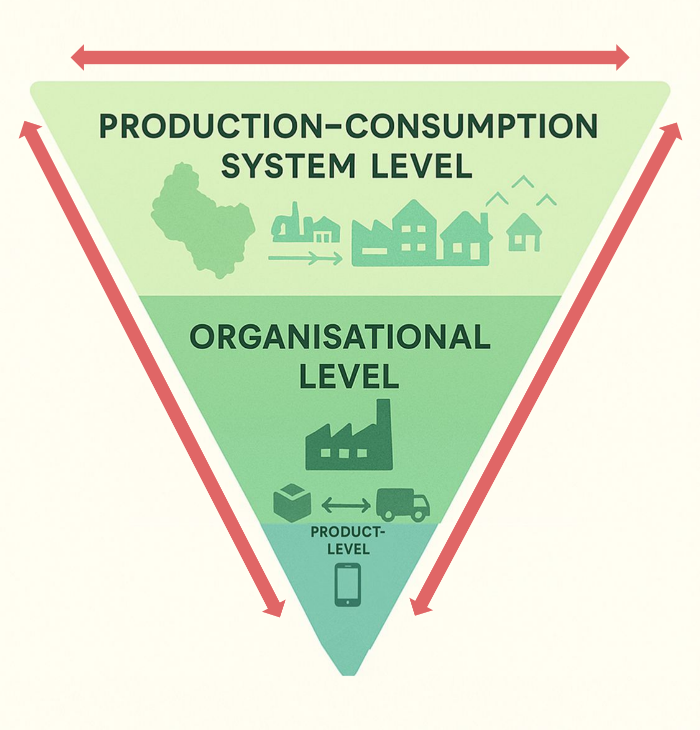
Scale and Agent Based LCA

ABM yields results that can be analyzed at multiple scales

ABM can help to bridge the gap between individual behavior and system behavior

Review of Existing AB-LCA studies
94% of studies include meso or macro scale systems (> city)
70% of studies mention using georeferencing

Source: Carrey et al. (in press)



Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Causality

Causality *refers to the cause-and-effect relationships between interventions affecting the sustainability impacts of consumption-production systems under study.*

In practice, modelling causality in LCA is challenging, due to gaps in data, feasibility issues and methodological constraints. No model is adequate at capturing all properties and mechanisms of the real world

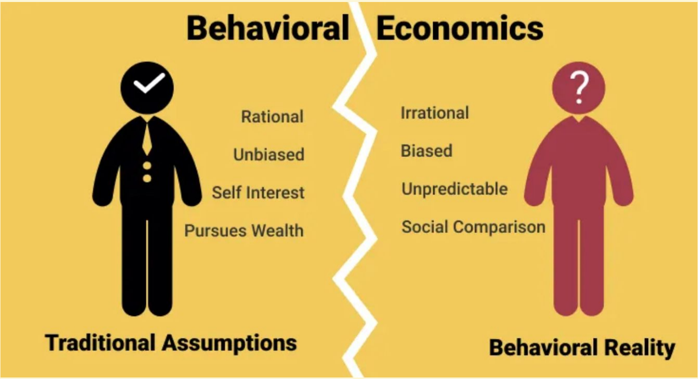


Figure: Hyeonbin Jung (2023) on medium.com

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Causality and Agent Based LCA

ABM can expand the economic rationality in consequential approaches, capturing more nuanced human behaviors

ABM facilitates modeling a wider range of interventions, such as public policies, business models, and physical designs, including those affecting behaviour.

Thus, AB-LCA expands policy analysis in LCA beyond technological and economic changes, encompassing other drivers of decision-making.

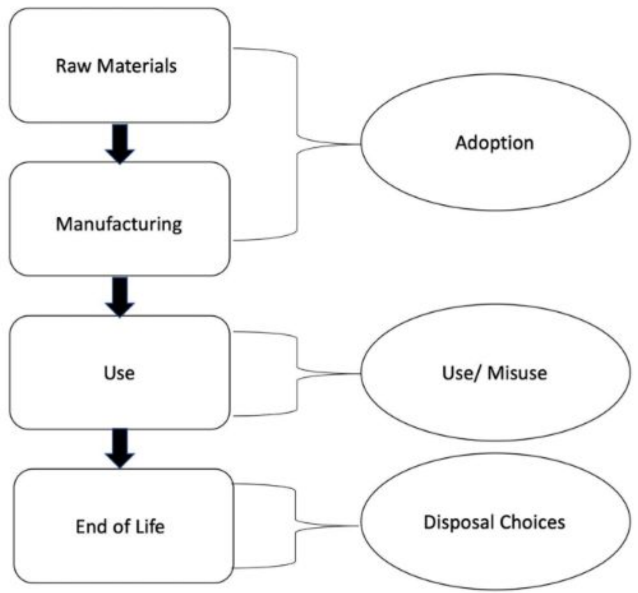
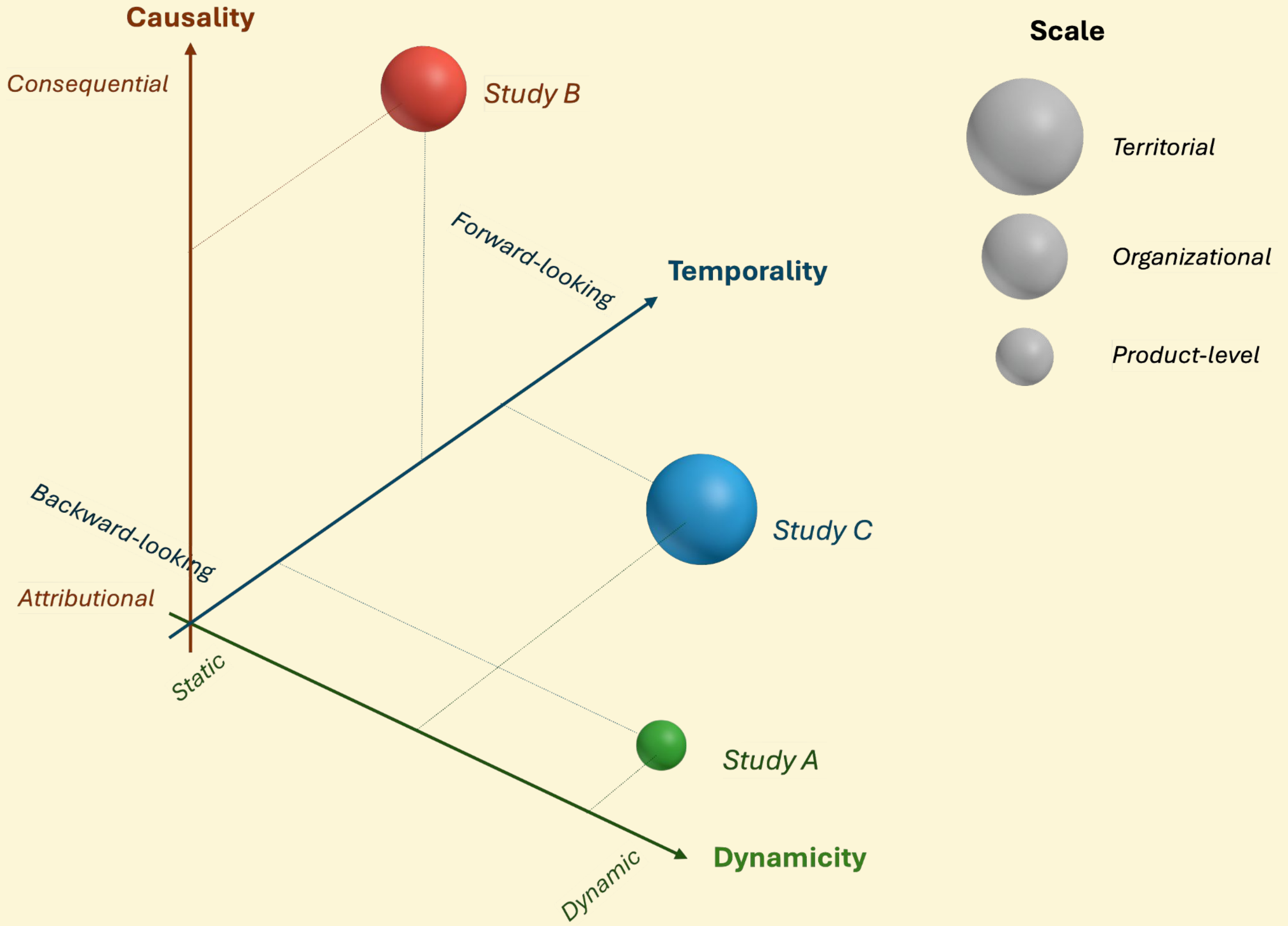


Figure 1. The role of human behavior at the different product stages of LCA adapted from (ISO, 2016a)

Figure: Hicks (2021)

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Flavours can be combined in AB-LCA



Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Paradigm shift of IE research by integrating agent-based modelling

Ryu Koide
National Institute for Environmental Studies (NIES), Japan

Beyond technological and economic causality

Systemic transformations require **behavioral shifts** and overcoming **inertia** of socio-technical systems (Markard et al. 2020; Sachs et al. 2019)

However, many LCA studies rely on **technocratic assumptions** and adopt narrow, myopic perspectives in terms of socio-technical transition

Review of Existing AB-LCA studies

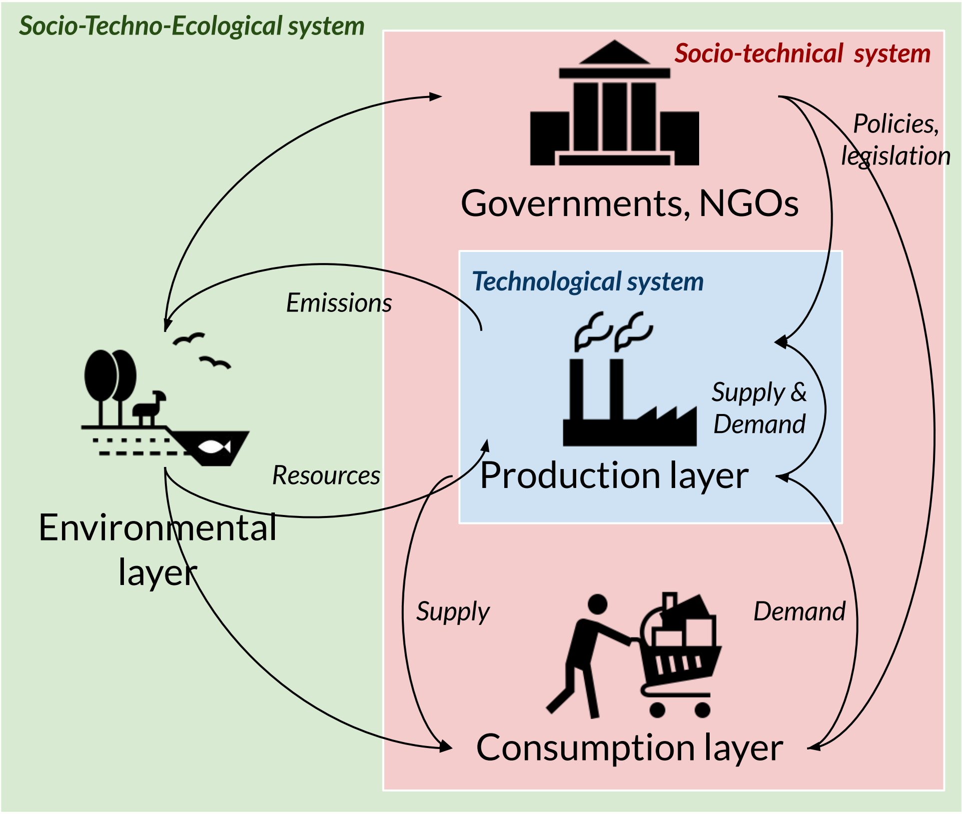
Types of scenarios:

Technological 64%

Institutional 39%

Behavioural 24%

Source: Carrey et al. (in press)



Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Beyond technological and economic causality

What are the realistic ways forward?

- Embedding behavioral and decision-making processes into LCI model is not straightforward — **complete agent-based digital twin is not feasible**
- Practitioners must **selectively represent system elements** as agents based on research objectives and judgment

For example:

- **For technological optimization**: modeling may appropriately emphasize physical causality (e.g., sustainable feedstocks for energy production) (Prasad et al. 2020)
- **For design of socio-technical systems:** modelling bidirectional influence of consumer and demand-side behaviors on the value chain (e.g., circular business models, mobility sharing services, industrial symbiosis) (Koide et al. 2023)

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Modelling policy interventions

	Conventional LCI Models	Agent-Based LCA
Policy	Direct changes in the technology matrix or demand vectors	Environmental parameters to influence agent behaviors
Influence on actor decisions	Assumed, not explicitly modeled	Endogenizes actors' responses to capture system-wide consequences
Suitable policy instruments	• Technology improvements • (Regulatory) • (Economic)	• Information • Economic • Regulatory • Others, Policy mixes

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Modelling policy interventions

Agent-Based LCA:

- Increasingly recognized for **simulating policy interventions to** support policymaking (Belfrage et al. 2024)
- Enables virtual **"what-if" experiments** for ex-ante policy design and ex-post evaluation (Gilbert et al. 2018)
- Consider **how actors (consumer, producers) perceive, adopt, or resist change** — influential factors of policy effectiveness (Wolf et al. 2015)
- Suitable for a variety of instruments and **exploring positive or negative synergies of policy mixes** (van den Bergh et al. 2022)

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

3 types of uncertainty (Bankes 2002)

(1) Probability distributions of key parameters

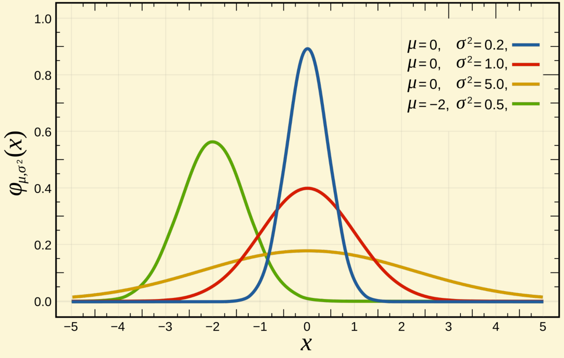


Figure: Wikipedia

(2) Conceptual models describing system interactions

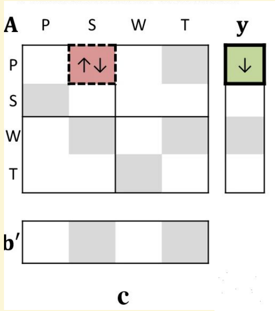


Figure: Aguilar-Hernandez et al. (2018)

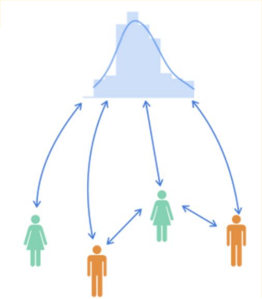


Figure: Beal Cohen et al. (2021)

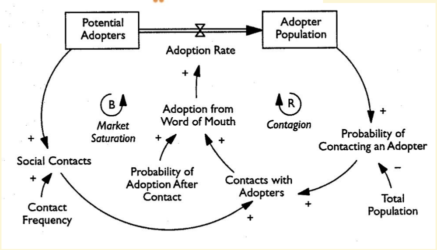


Figure: Sterman (2002)

(3) Disagreements on how to assess the desirability of outcomes

Figure: Gimenez et al. (2019)

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Recommendations for AB-LCA modellers

Why? – Clarify the purpose of incorporating ABM

Temporality: *Prospective or retrospective?*

Dynamicity: *System change dynamically? Impacts dynamic?*

Scale: *Per product? territorial impacts? Organisations or households?*

Causality: *Techno-economic enough? Social agents play roles?*

How? – Locate your ABM in existing taxonomy of integration techniques

(Micolier et al. 2019; Baustert and Benetto 2017; Fuortes et al. 2025)

Direction of change: *LCA feedback to ABM? ABM modifies LCA background?*

Integration method: *Soft or tight coupling? Hard coupling? Surrogate modelling?*

Software: *Which platform? Combination of platforms?*

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Recommendations for AB-LCA modellers

Which system? – Identify elements of the target system that contain complexity

As system complexity increases, the stronger the need for causal (consequential) modelling

Functional unit in ABM depends on a point of observation

Which interventions? – Identify key interventions and consider modelling approaches

The greater the emphasis on behavioural and social aspects, the more central the role of ABM

How uncertain? – Uncertainty not only involves parameters but also model structure

Consider sensitivity analysis of model structures

Decision-making under deep uncertainty methods can provide guidance (McPhail et al. 2018)

Source: Koide, Larrea-Gallegos, Cohen, Ding, Bączyk, Lange: What can Life Cycle Assessment modeling gain from Agent-Based modeling? (under review)

Summary

1. **Introduction**
   What is complexity and why we care about it.

2. **ABM and LCA**
   ABM can enhance different flavors of LCA

3. **A paradigm shift**
   Recommendations have been provided

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Follow-up working session

For those interested in contributing to the initiative
5th December 10:00 AM Central European Time

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Thank you!

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