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ENV 501 / GR A3 30

Material Flow Analysis and resource management

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Fall 2024

Laboratory on Human-Environment Relations in Urban Systems

Last week

- Understand the relationship between MFA, policy and the public
- Understand MFA as a tool for bridging disciplines
- From Material Flow Analysis to Material Flow Management
- The Human-Environment System (HES) framework
- Know how MFA can be combined with social science approaches

Course outline

Block	Week	8:15 - 9:00 and 9:15 - 10:00		13:15 - 14:00	14:15 - 15:00
Block I: EW-MFA global / national	W1 - Sep 12	Introduction to the course and general concepts	All	Exercise	Project
	W2 - Sep 19	EW – MFA and EW – MFA in different countries	FMC	Exercise	Project
	W3 – Sep 26	EW – MFA in the Swiss context, Urban Metabolism	External Guest – Florian Kohler	Exercise	Project
	W4 - Oct 03	EW – MFA in the Swiss context: Cantons and Circular Economy	FMC	Exercise	Project
Block II: MFA regional / urban	W5 - Oct 10	The Service-Stock-Flows Nexus	CRB	Exercise	Project
	W6 - Oct 17	Dynamic MFA	External Guest – Stefan Pauliuk	Exercise	Project
	Oct 24	Autumn break			
	W7 - Oct 31	Spatial MFA	FMC	Exercise	Project
	W8 - Nov 07	Input-Output Analysis and Material Flow Cost Accounting	External Guest – Vincent Moreau	Exercise	Project
	W9 - Nov 14	MFA and Uncertainty	External guest – Stefan Pauliuk	Exercise	Project
	W10 - Nov 21	Case studies: Waste management in Indonesia / Critical Raw Materials in the Swiss context	GF & FMC	Exercise	Project
Block III: Social sciences and public policy	W11 - Nov 28	Social Metabolism	CRB	Exercise	Project
	W12 - Dec 05	Agent-based model	CRB, FMC, MAH, SLC	Past exam	Project
	W13 - Dec 12	Group Project Presentation	CRB, FMC, MAH	Project	Project
	W14 - Dec 19	Group Project Presentation	CRB, FMC, MAH	Project	Project

Content of the lecture

- Understand the key characteristics of Agent-Based Models (ABM) and their application fields
- Recognize the purpose of ABMs in Industrial Ecology
- Learn about the differences of MFA and ABM and understand the added value of using ABM in Industrial Ecology research
- Recognize how ABM can be used for spatial energy planning

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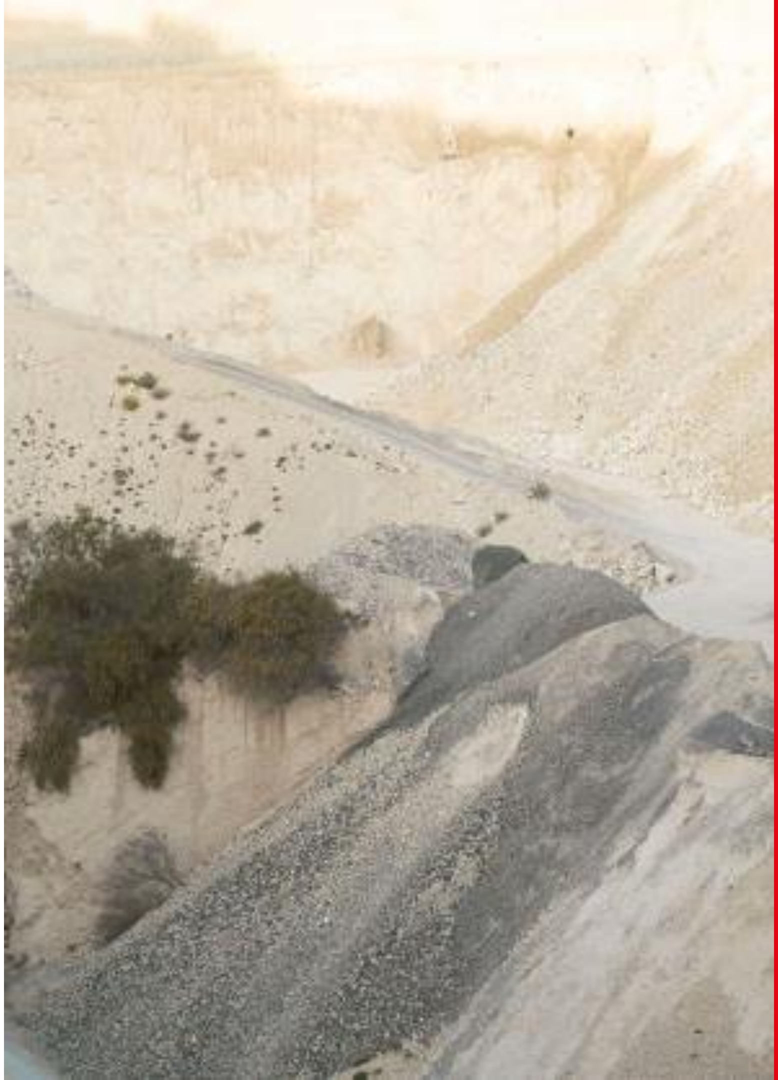

Agent-Based Modelling and applications fields

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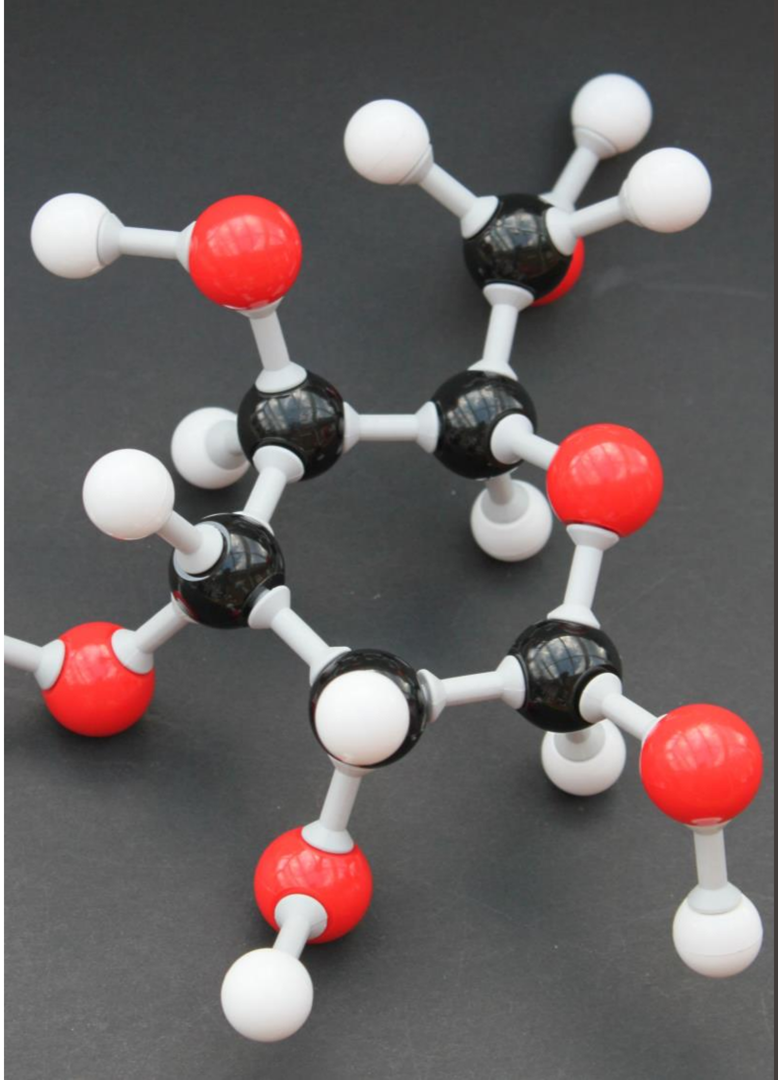
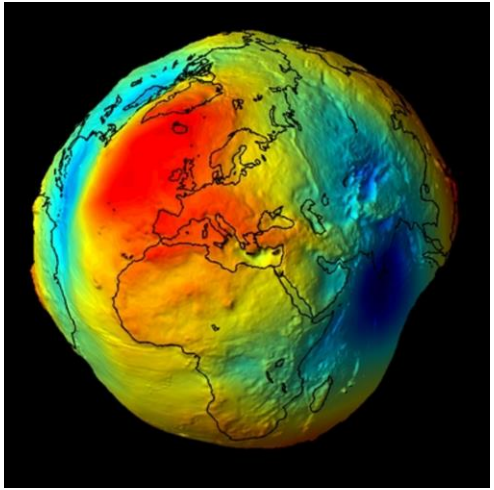


Models

What is a model?

A model is a simplified representation of reality.



*"(…) all models are approximations. Essentially, **all models are wrong, but some are useful**. However, the approximate nature of the model must always be borne in mind."*

George Box
Empirical Model-Building and Response Surfaces (1987)

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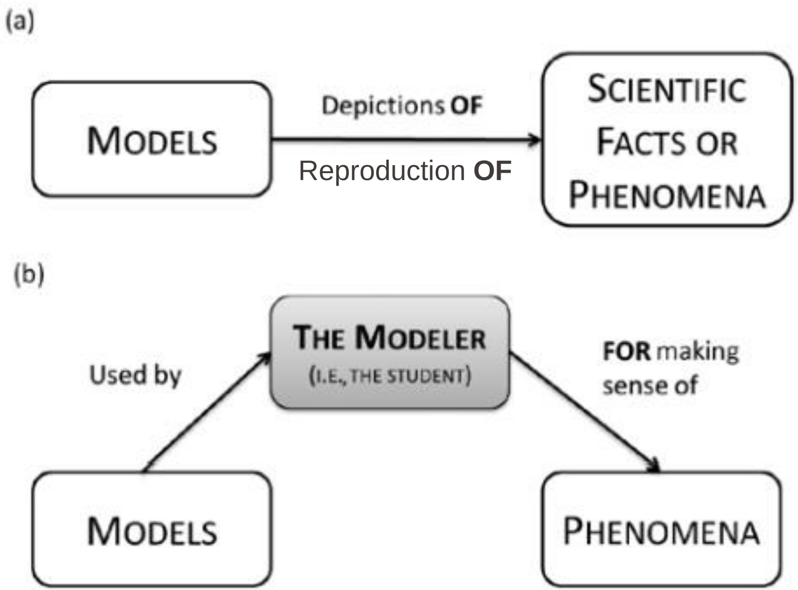
The difference between models *of* and models *for*



Schwarz et al. (2017)

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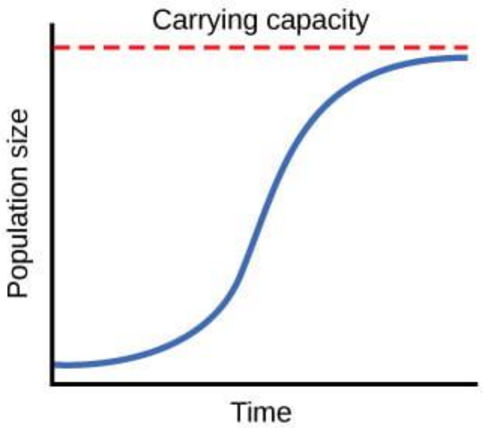
Different types of models

Physical models

Source: Atlas Obscura

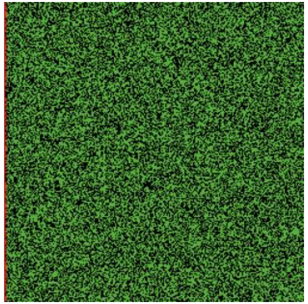
Mathematical models

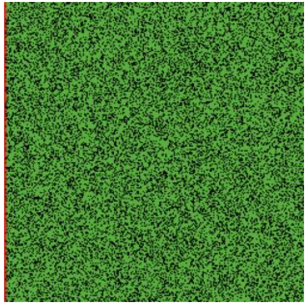


$$\frac{dN}{dt} = rN\left(\frac{K-N}{K}\right)$$

Source: OpenStax Biology

Computational models





Source: NetLogo Models Library

Bonabeau (2002), Wilensky & Rand (2015)

What a model is <u>NOT</u>

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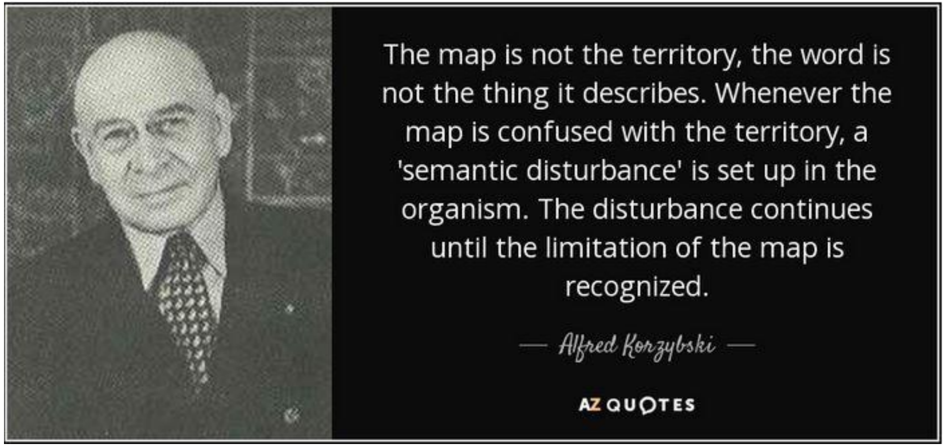
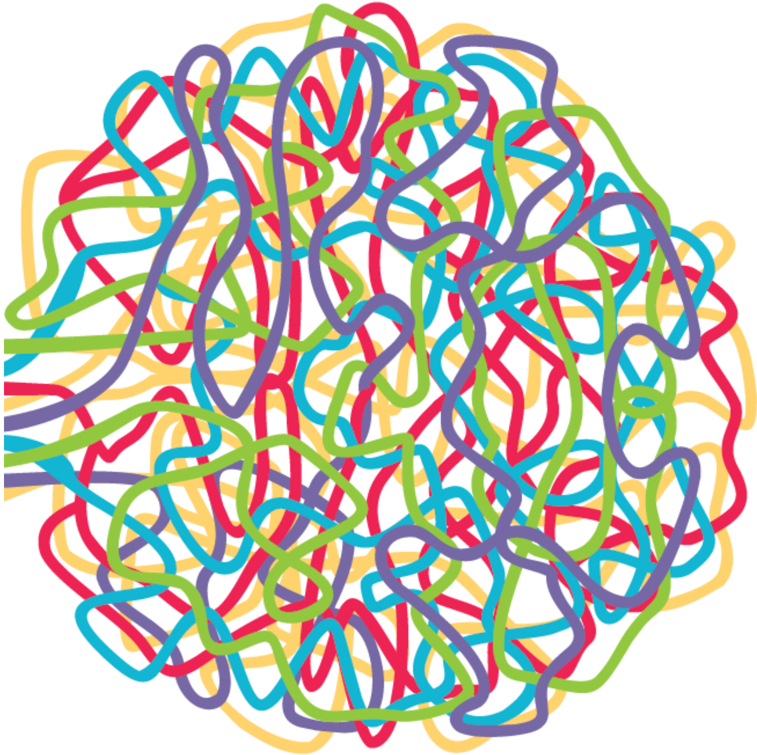
- Models are abstractions—**<u>not</u> exact replicas of reality**
- Models are influenced by assumptions—**<u>not</u> free from bias**
- Models provide insights into trends—**<u>not</u> perfect predictions**
- Models are tools—**<u>not</u> truth machines**



Box (1987)



Complex systems

What is a complex system?

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A complex system is an ensemble of many elements which are interacting in a disordered way, resulting in robust organisation and memory.

- However:
  - There is no concise definition of a complex system
  - These five ‘necessary’ and ‘sufficient’ conditions provide a physical account of complexity
  - Yet some of them are neither necessary nor sufficient

Ladyman, Lambert, & Wiesner (2013)

Core features of complex systems

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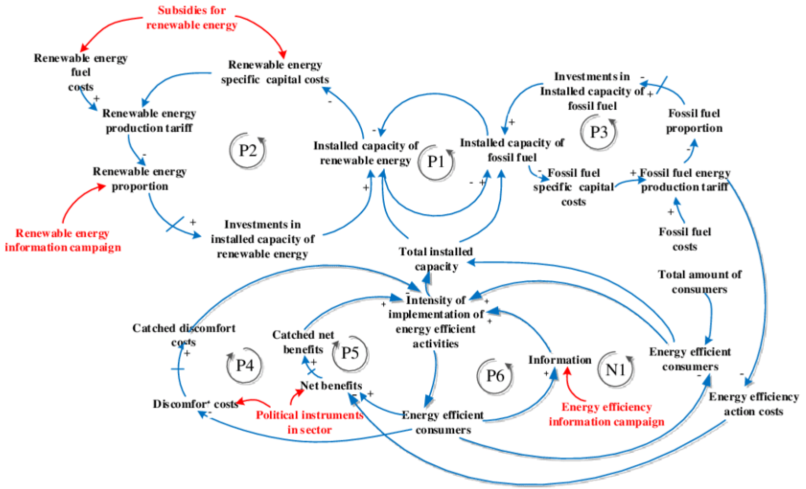
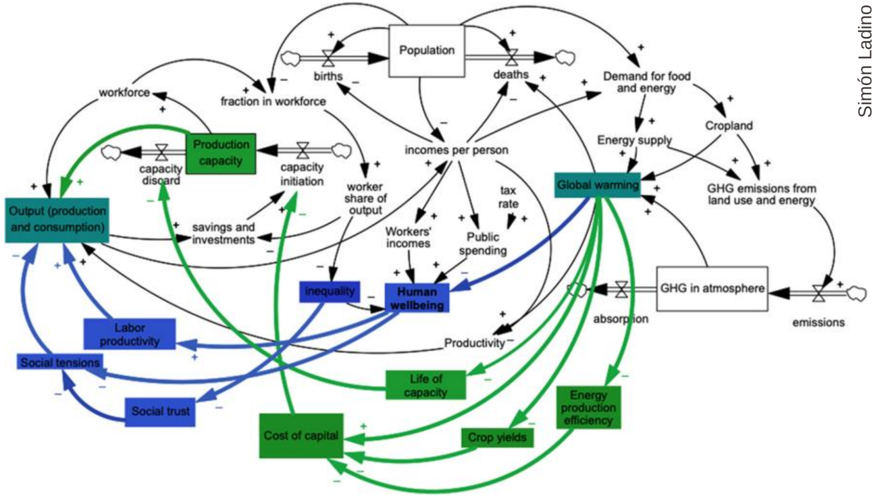
1. **Nonlinearity**: Small changes can lead to large, unpredictable effects.
2. **Feedback loops:**
   - Positive (reinforcing) feedback: Amplifies change.
   - Negative (stabilizing) feedback: Stabilizes the system.
3. **Emergence:** Macro-level patterns arise spontaneously from micro-level interactions.
4. **Adaptation:** Systems change based on internal/external influences and past experience.
5. **Robustness:** Order is stable under perturbations of the system, given its distributed nature and lack of central control.

Ladyman, Lambert, & Wiesner (2013), Holland (1992)

Casual Loop Diagrams

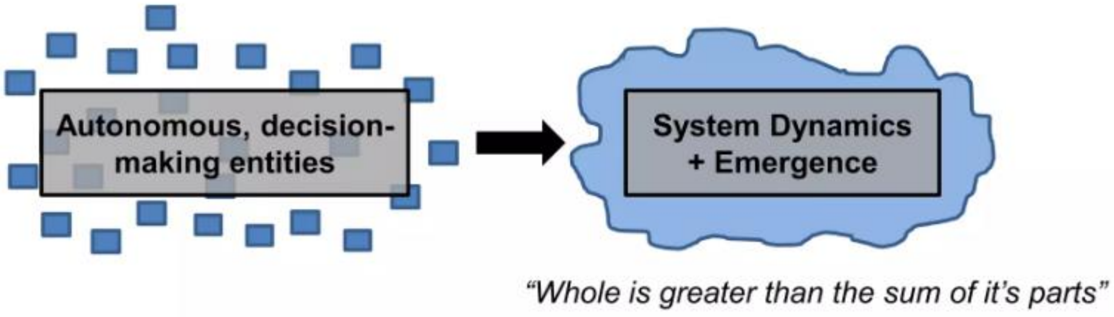


Source: Lauka et al. (2015)



Source: Callegari, Collste, & Feder (2024)

Complex Systems



Source: Colossal

Source: Dribble

Source: Dribble

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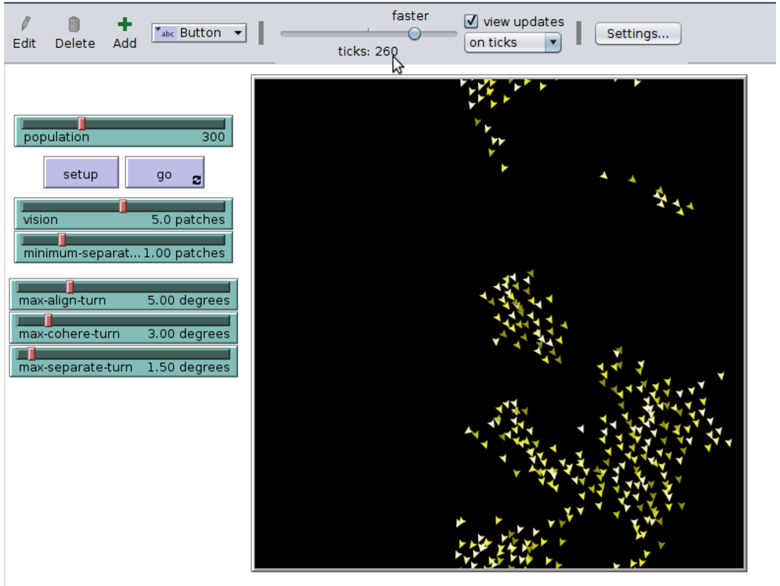
Agent-based Modeling

What is Agent-Based Modeling?

- **Computational modeling approach** where systems are modeled as collections of autonomous, interacting agents.
- ABMs simulate behaviors **based on rules at the micro-level** to observe macro-level outcomes.
- ABM is the idea that the world can be modeled using **agents**, an **environment**, and a description of **agent-agent and agent-environment interactions**



Source: NetLogo Models Library

Epstein & Axtell (1996), Wilensky & Rand (2015), Axelrod (1997), Reynolds (1987)

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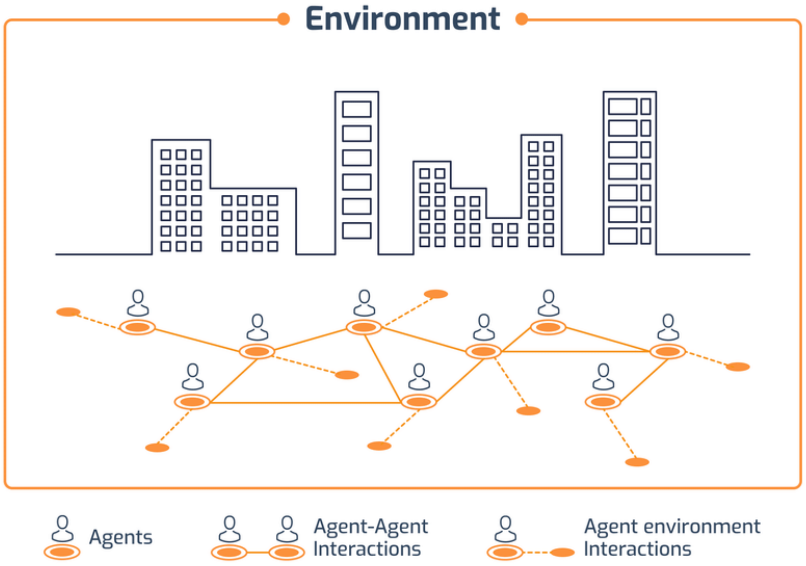
Key characteristics of ABM

Components:

- **Agents**
- **Environment**
- **Interactions**

Features:

- **Heterogeneity**
- **Bottom-up**
- **Flexibility**
- **Time dependency**



Source: Ramadiah, Galbiati, & Soramaki (2021)

Bonabeau (2002), Wilensky & Rand (2015), Grimm & Railsback (2005)

Why to use ABM?

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- **Captures complexity:** Models heterogeneity and emergent phenomena that traditional methods cannot.
- **Scenario testing:** Simulate scenarios to test policies or interventions.
- **Behavioral realism:** Models decisions at the individual level, grounded in behavior and interactions.

Criteria	Equation-based Modeling	Agent-based Modeling
Theoretical foundation	High, theory-driven	Low, data-driven
Direction of approach	Top-down, aggregate	Bottom-up, disaggregate
Expression	Mathematical equations	Programming language
Techniques	Statistics	Neural networks, big data analytics
Compute requirements	Minimal	Intensive
Network structure	No	Yes
Assumptions about individuals	Homogeneous	Heterogeneous
Assumptions about interaction among individuals	No/invisible	Yes/visible
Representation of time	Continuous	Discrete
Temporal dynamics	Static	Dynamic
Appropriate domain	Simple, global, dominated by physical laws	Complex, high degree of localization, dominated by discrete decisions

Source: Kwon & Silva (2019)

Epstein & Axtell (1996), Wilensky & Rand (2015), Axelrod (1997), Reynolds (1987)

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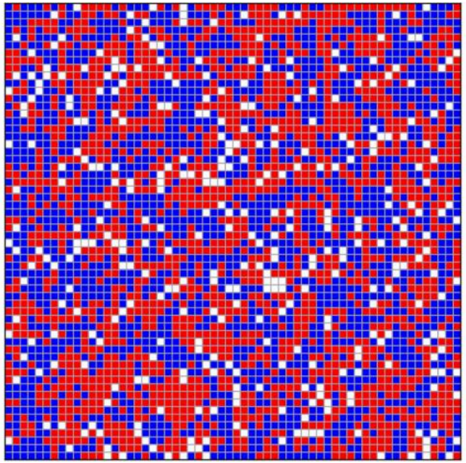
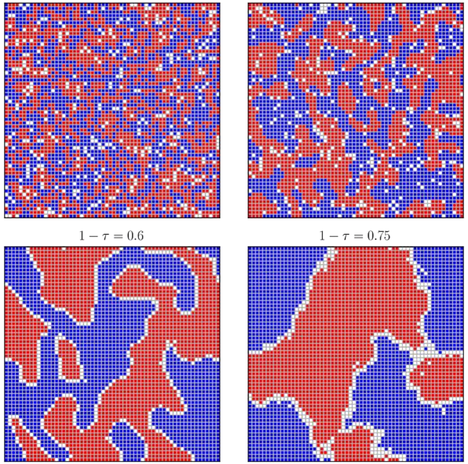
Applications of ABM

- **Social Systems:**
  - Segregation model (Schelling, 1971)
  - Social contagion models
- **Epidemiology:**
  - Pandemics spread modeling (Epstein, 2009)
- **Urban Planning:**
  - Simulating traffic flow and urban growth
- **Energy Systems:**
  - Modeling renewable energy adoption at the household level





Source: Mingarelli (2021)

Wilensky & Rand (2015)

ABMs have limitations

High Computational Cost. Large-scale ABMs with many agents and complex interactions require significant computational resources.

Dependency on Assumptions. The accuracy of an ABM relies heavily on the validity of assumptions about agent behavior and interactions.

Data Requirements. High-quality data is often needed to define agent characteristics and interactions.

Validation. Emergent phenomena at the macro level may not have direct empirical counterparts for comparison.

Interpretation. Emergent outcomes can be difficult to interpret, especially for non-expert audiences unfamiliar with ABM modeling.

Scalability/Reproducibility. Scaling up ABMs or reproducing them to other contexts can introduce errors or oversimplifications.

Holland (1999), Bonabeau (2002), Sterman (2000), Wilensky & Rand (2015)

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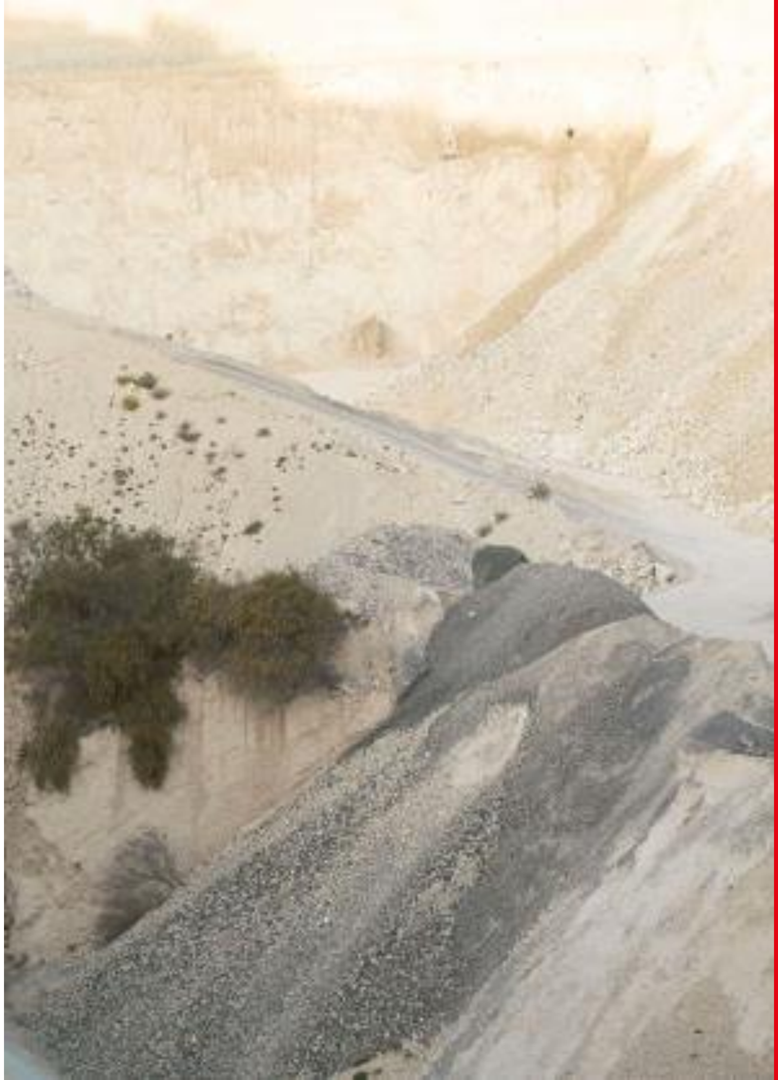

Integrated MFA in Industrial Ecology

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Purpose of MFA in Industrial Ecology

- **Descriptive assessments:** Description of past or current flows and stocks of materials in a spatial and temporal defined system (e.g., EW-MFA).
- **Prospective assessments:** Assessment of potential impacts of future changes on material systems.
- MFA is increasingly integrated with other methods from different research fields to assess and improve the sustainability of material systems.

Baars et al. 2022

Purpose of integrated MFA

- To include economic, social, and environmental layers.
- To include economic mechanisms and link the economic system to the material system.
- To include dynamics, feedbacks, and behavior based on simulation and optimization methods.
- To assess environmental impacts of material stocks and flows.

Baars et al. 2022

Integrated MFA

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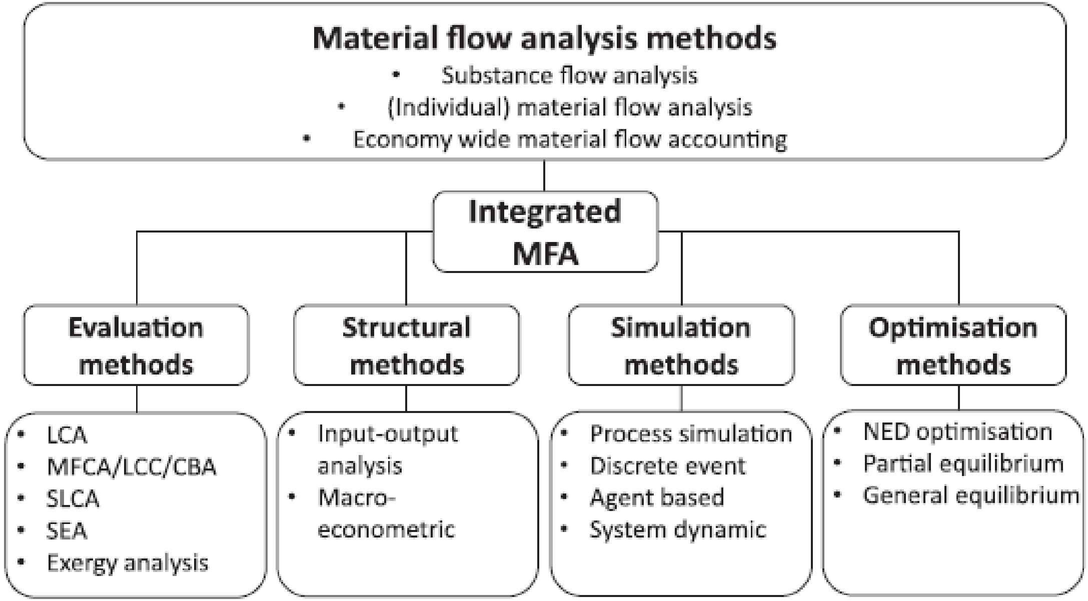

FIGURE 2 Possible methods integration for prospective MFA by method family. LCA = life cycle assessment; MFCA = material flow cost analysis; LCC = life cycle costing; CBA = cost benefit analysis; SLCA = social life cycle assessment; SEA = statistical entropy analysis; NED = non-elastic demand optimization; MFA = material flow analysis

Baars et al. 2022

Purpose of integrated MFA

TABLE 1 Categorizations of methods and purposes of integrated MFA

Category	Method	Purpose of integration
Evaluation	Life cycle assessment	Environmental emissions related to material flows; improve resource-related life cycle impact assessment
	Life cycle costing	Economic feasibility of material efficiency-related strategies on a product level
	Cost benefit analysis/discounted case flow	Economic feasibility of material efficiency-related strategies on product and regional level
	Material flow cost accounting	Evaluate and identify material cost savings in companies and supply chains
	Social life cycle assessment	Social impact related to the material system
	Statistical entropy analysis	Evaluate the dilution or concentration of substance and materials based on relative statistical entropy
	Exergy analysis	Evaluate the availability of energy stored in material flows (exergy)

Baars et al. 2022

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Purpose of integrated MFA

Simulation	Discrete event	Discrete simulation of material flows in the material systems
	Agent based	Simulation of material flows driven by the interaction of supply chain actors based on clearly defined rules
	System dynamics	Simulation of material flows driven by a global system behavior–based on differential equations
	Process simulation	Simulation of individual process in a more detailed manner based on thermo-dynamic valid relations
Optimization	Non-elastic demand optimization	Identify optimal system configurations based on one or several objective functions when several production alternatives are possible, demand is exogenous and fixed
	Partial equilibrium	Simulate material markets based on endogenous demand and supply interaction, limited to one or few economic sectors
	General equilibrium	Similar to partial equilibrium but includes all economic sectors
Structural	Input-output analysis	Physical flows of one or several economic sectors based on conversion of monetary IO tables using scenarios or dynamic IO to forecast material flows
	Macro-econometric	Based on econometric relation of IO tables used to model future material flows and the impacts of policies

Baars et al. 2022

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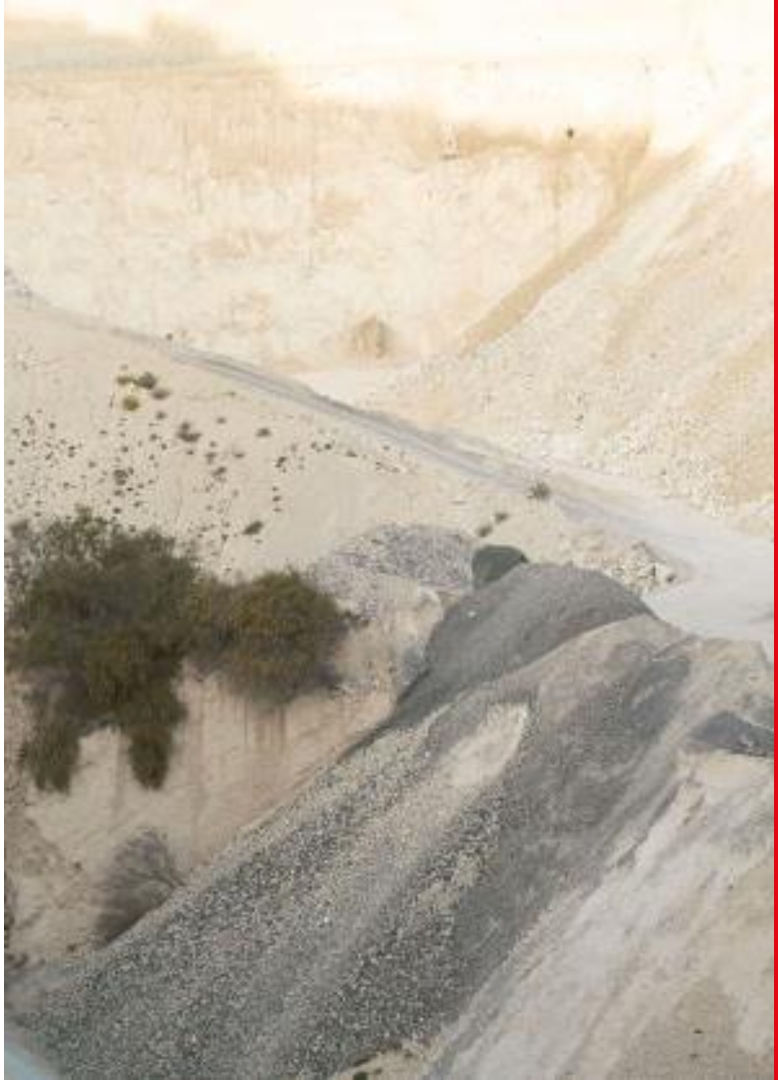

Potentials of ABM in Industrial Ecology

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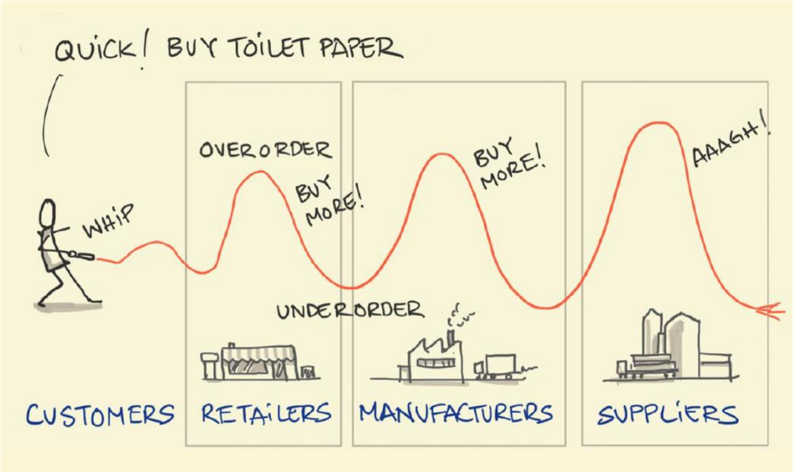
Why do we need ABM in Industrial Ecology?



- Industrial Ecology studies the systemic relationships between society, economy and natural environment.
- These dimensions are interconnected through production and consumption systems.
- These systems are complex since they are highly intertwined networks that result from human interaction.

Gustavo Larrea, Industrial Ecology Day, 2024

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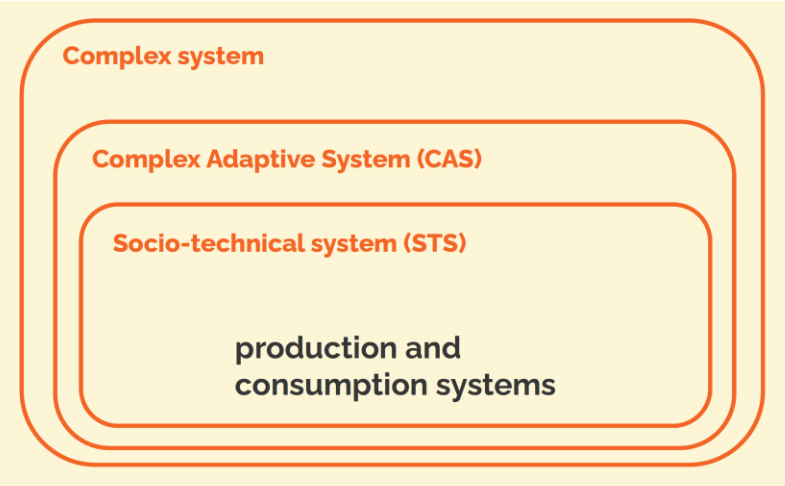
Production and consumption systems are complex



- **Complex systems** consisting of an assembly of elements interacting with each other.
- **Adaptive systems** as they respond to exogeneous and endogenous changes.
- **Socio-technical systems**, and not only technological systems, as they are networks of social agents.

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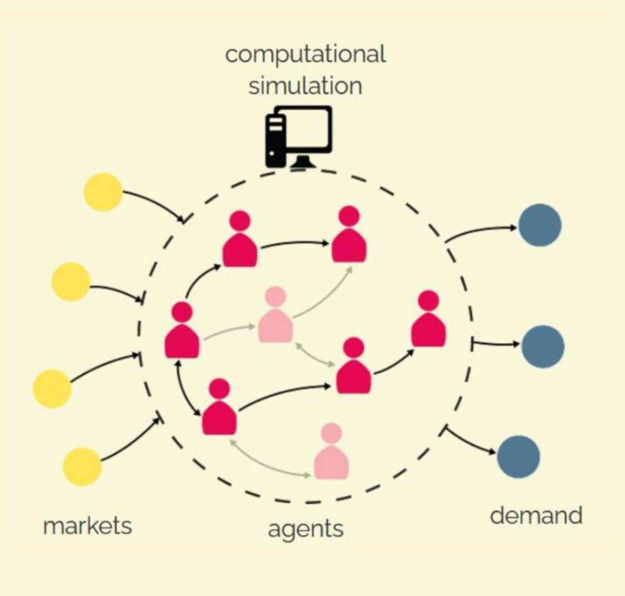
ABM in Industrial Ecology



- Production and consumption systems are **complex socio-technical systems.**
- Studying these systems can be challenging due to **heterogeneous patterns, non-linear dynamics and emergent behaviors** of consumers and stakeholders.
- ABM in Industrial Ecology is taking momentum and is far from being mainstream.

Gustavo Larrea, Industrial Ecology Day, 2024

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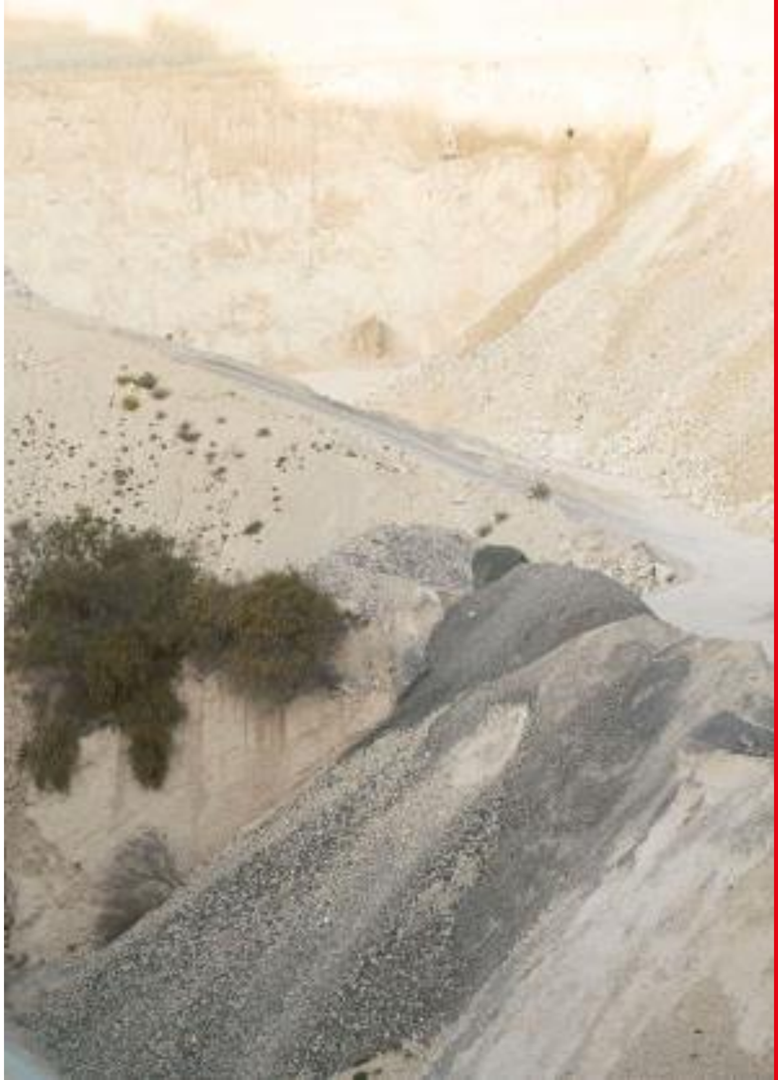

Comparison of ABM and MFA

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Why combine MFA and ABM?

Material Flow Analysis

- Tracks flows and stocks of materials within a system.
- Quantitative method for understanding resource demand and waste generation.

Agent-Based Modelling

- Simulates behaviors and interactions of individual “agents” (e.g., consumers, companies, entities).
- Allows for emergent, complex dynamics driven by decision-making.
- Useful for understanding adoption, usage patterns, and the impact of policies.

Key differences

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Aspect	Dynamic MFA	ABM
Focus	Material flows and stocks	Agent behaviors and interactions
Granularity	Aggregated, system-level	Individual, behavior-based
Temporal Dynamics	Gradual changes, lifecycle-based	Non-linear, adaptive changes
Data Needs	Historical material flow data	Behavioral, qualitative data

Key benefits of linking MFA and ABM

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Behavior-driven updates

ABM informs MFA with realistic adoption rates and behavior patterns.

Adaptive feedback loops

MFA outputs (e.g., material scarcity) can influence ABM agents' decisions.

Enhanced policy modeling

ABM provides insights into how policy scenarios might alter material demands or recycling rates over time.

Case study: Circular Economy and Resource Recycling

Model recycling behaviors and resource use in a city's circular economy

- **MFA:** Tracks materials like plastics estimating available stocks for recycling.
- **ABM:** Models consumer, business, and waste management behaviors in recycling decisions.
- **Linked outcome:** ABM shows recycling adoption under different incentives, informing MFA on recycled material stock over time.

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Case study: Electric Vehicle (EV) Adoption and Battery Demand

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Forecast material needs for EV batteries over time

- **MFA:** Tracks material flows (e.g., lithium, cobalt) through EV batteries.
- **ABM:** Simulates consumer EV adoption decisions influenced by incentives, social factors, and battery costs.
- **Linked outcome:** ABM provides dynamic EV adoption rates, enabling MFA to estimate changing battery material demand.

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Guiding questions for your MFA project

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- Are there **dynamic or behavioral aspects** in the system (e.g., decision-making, market trends, policy impacts) that MFA alone cannot fully capture?
- What specific **agents or stakeholders** (e.g., consumers, industries, policymakers) are relevant to your case, and how do their actions influence material flows?
- Is there a need to analyze **feedback loops**, such as how material availability might affect agent decisions, or vice versa?
- What kinds of **heterogeneity** (e.g., income levels, preferences, access to resources) exist among agents, and how might these differences shape outcomes?
- What **outputs** from the ABM (e.g., agent decisions, adoption trends) can serve as **inputs** for your MFA (e.g., material inflows/outflows)? Conversely, how can MFA inform your ABM?
- How can the combined MFA-ABM approach help identify **leverage points** for improving material efficiency or sustainability?

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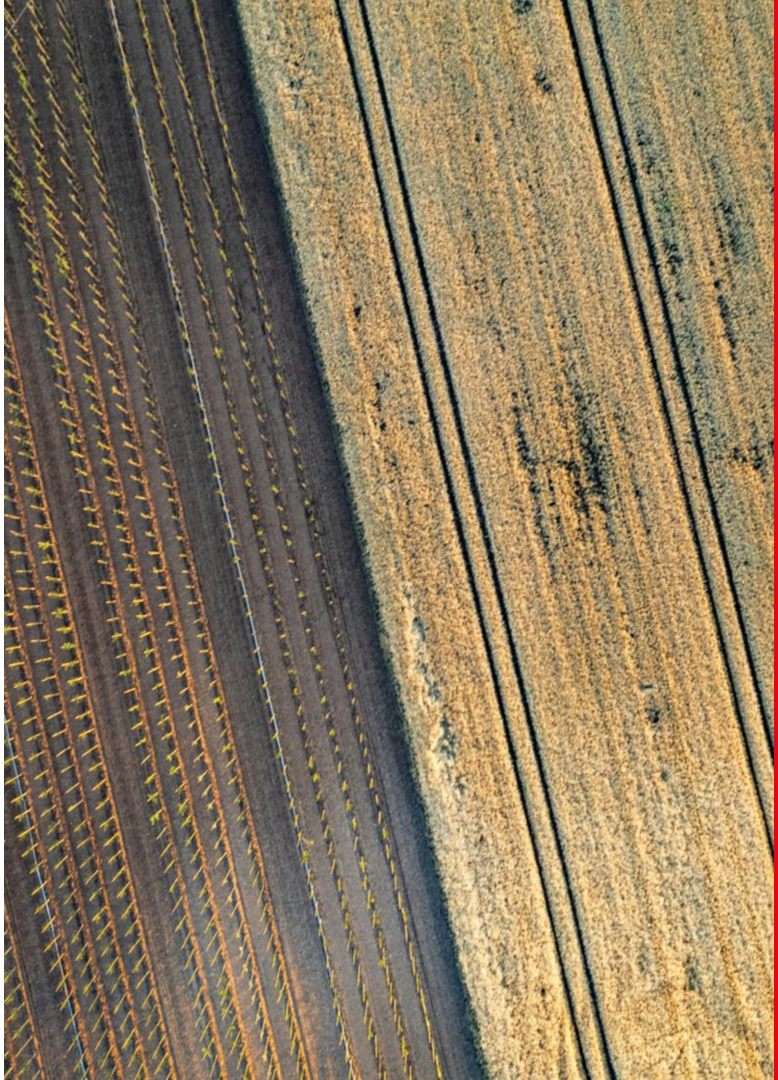

Coupling ABM with Territorial LCA to support agricultural land use planning

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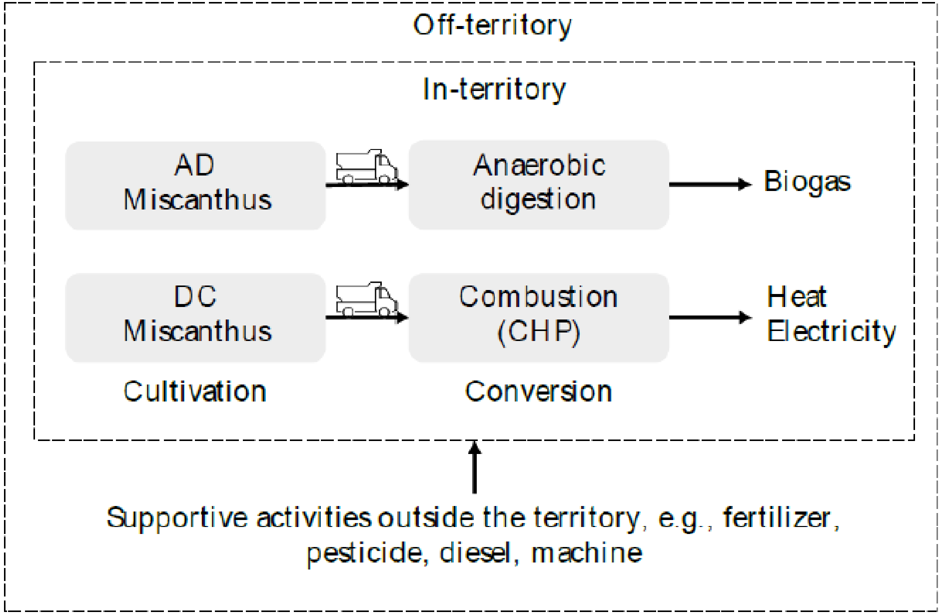
Agricultural land-use planning in Wallon region, Belgium



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Denial of bioenergy crops

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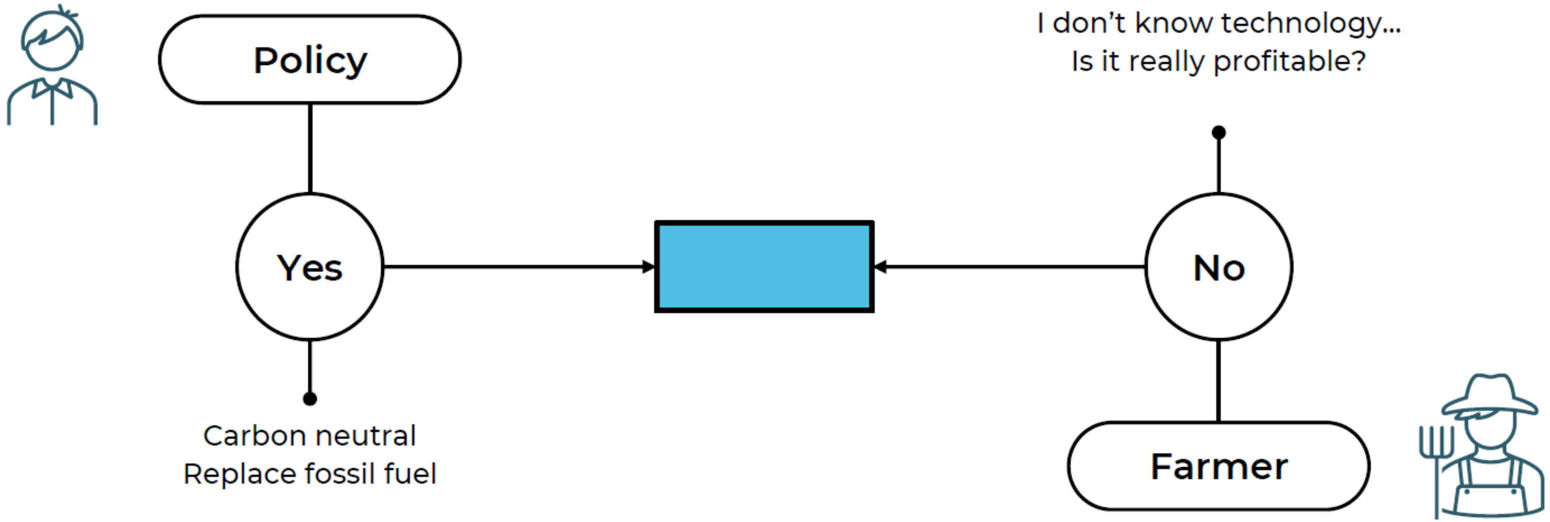

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Adoption of bioenergy crops through financial incentives

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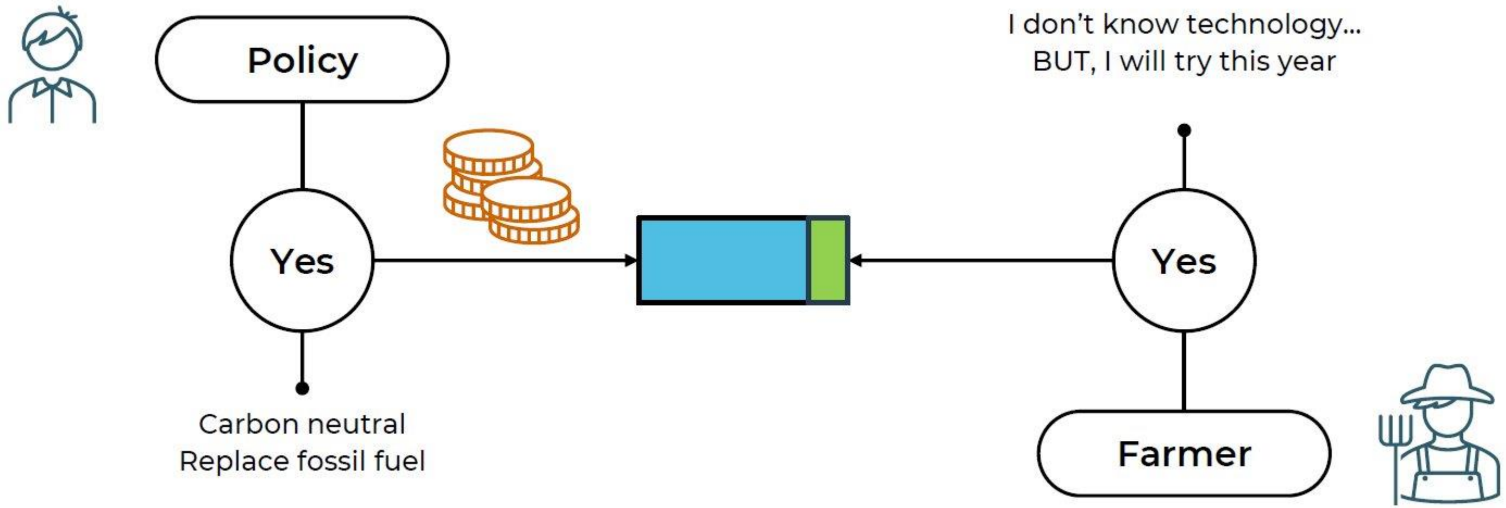

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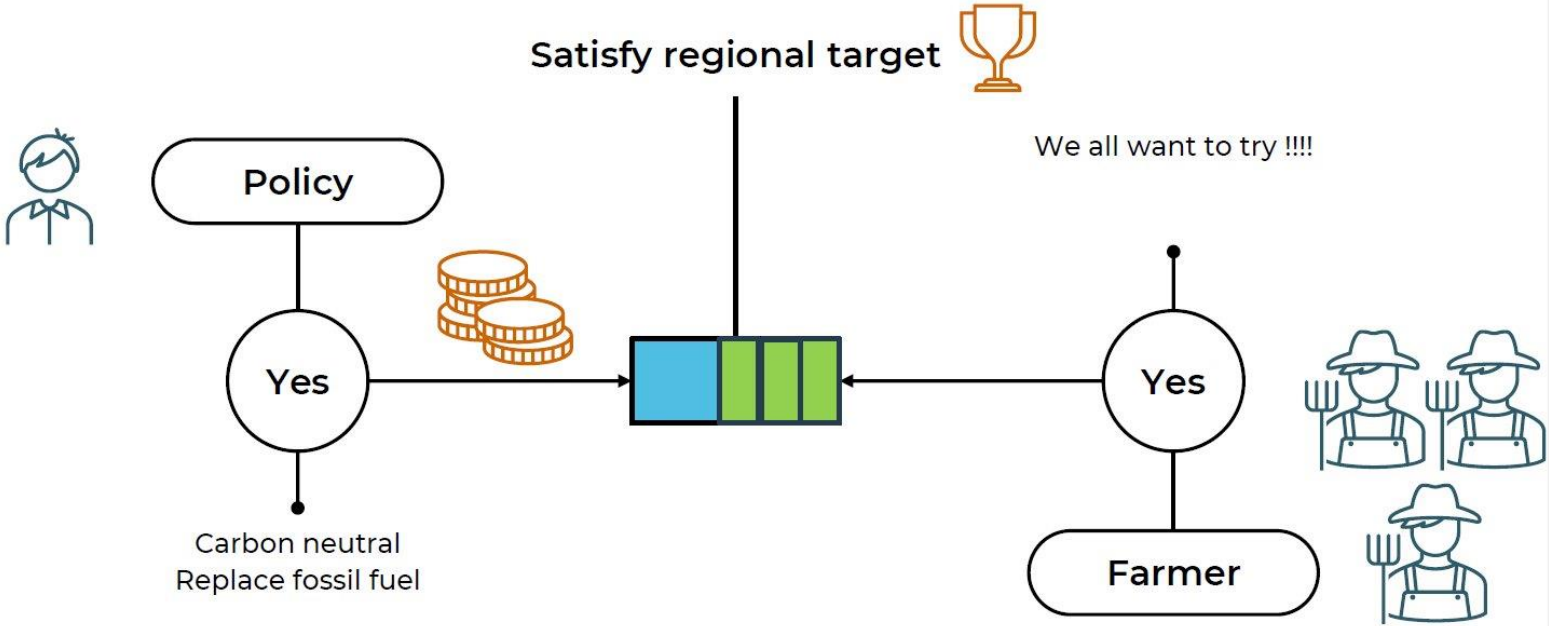
Ideal scenario to satisfy regional target



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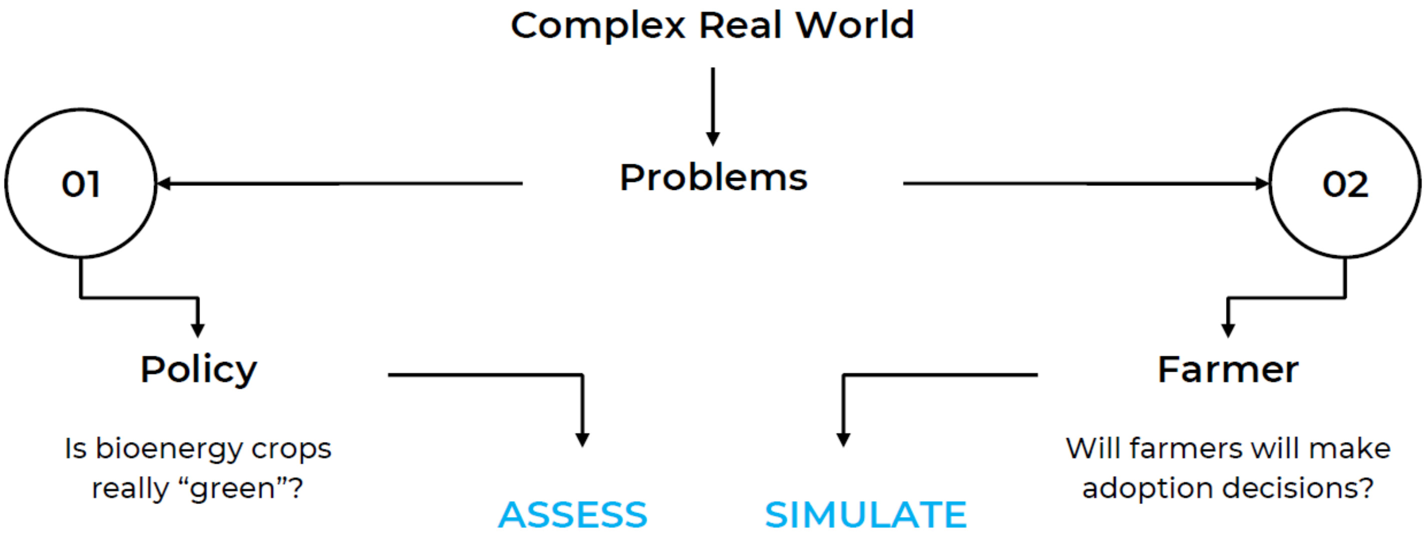
Impact assessment and simulation is needed



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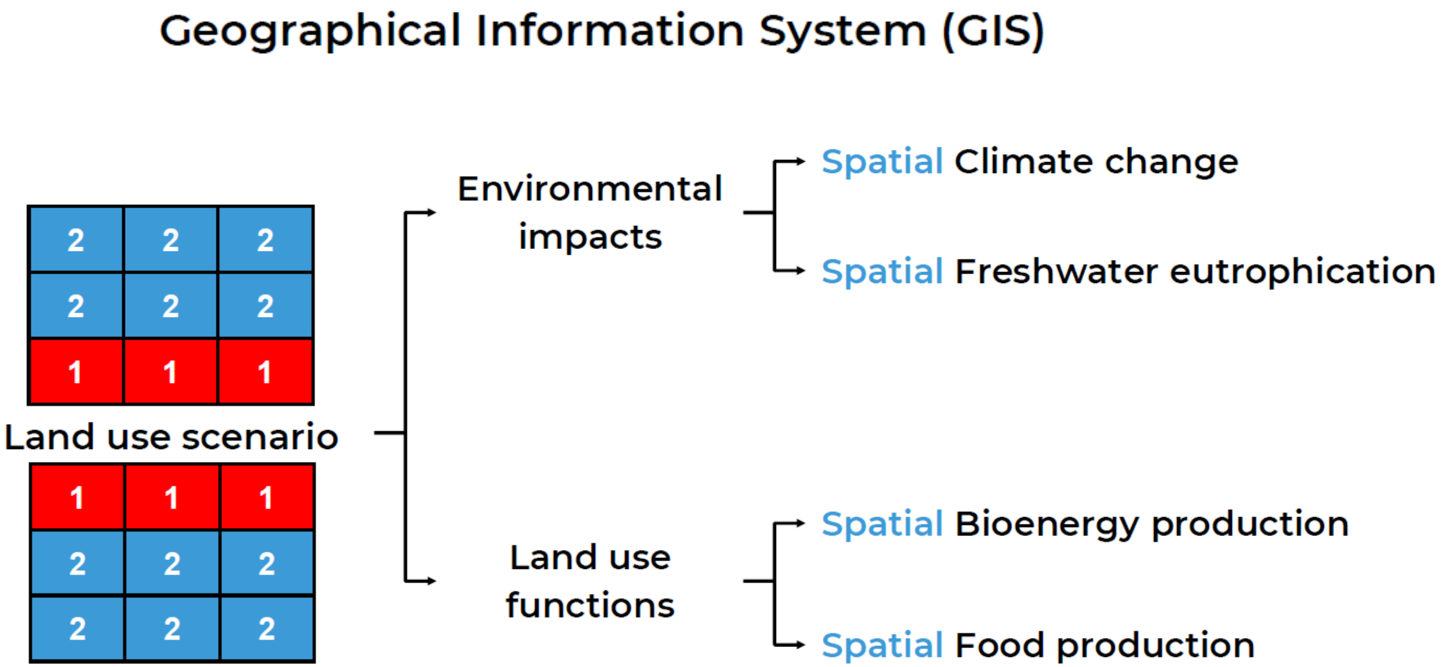
Spatial Territorial LCA



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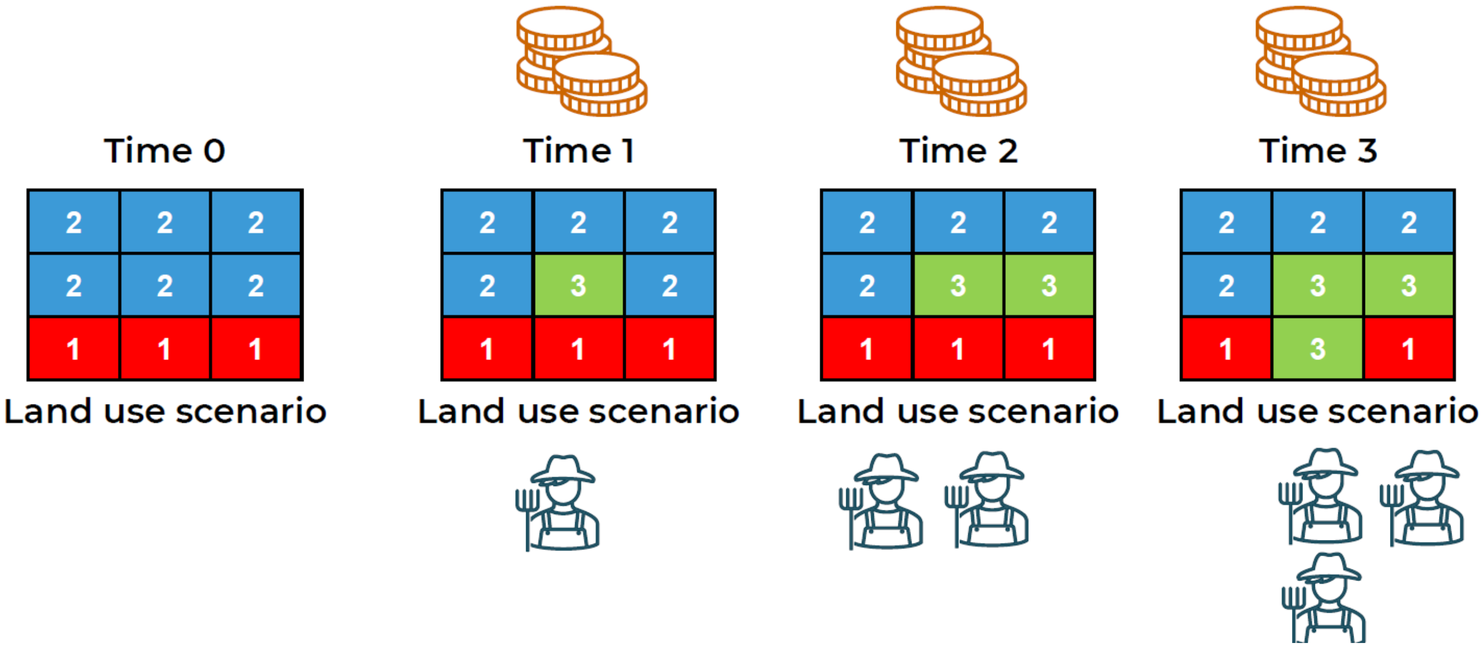
Land use change over time based on farmers' decisions



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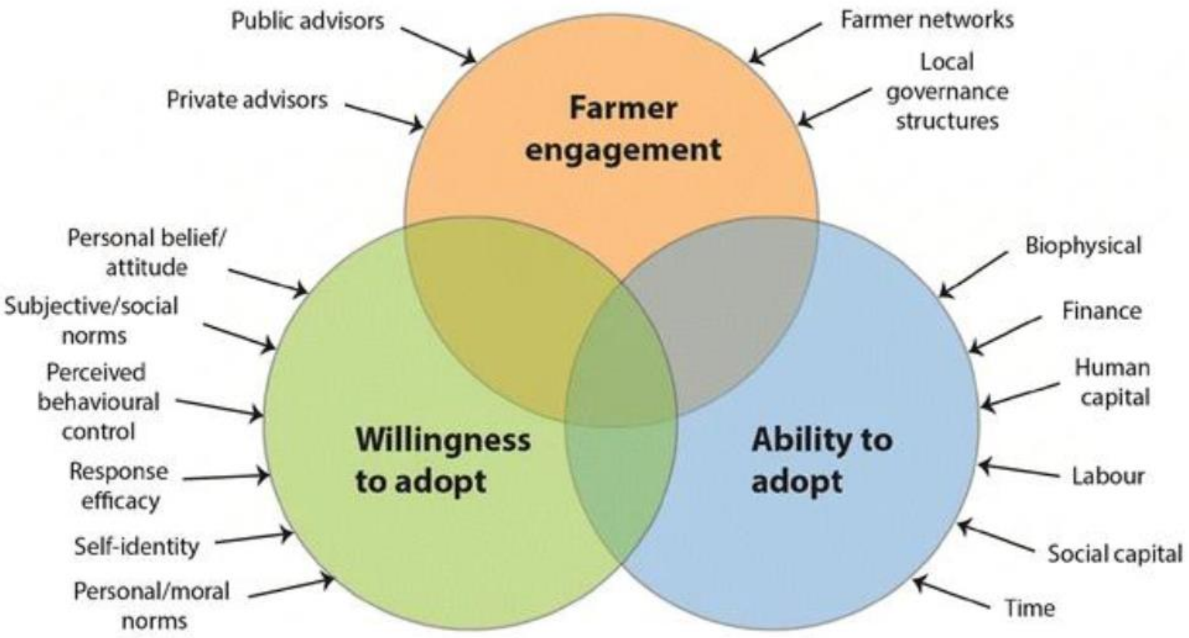
Factors influencing farmers decision



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Farmers' decision-making in ABM

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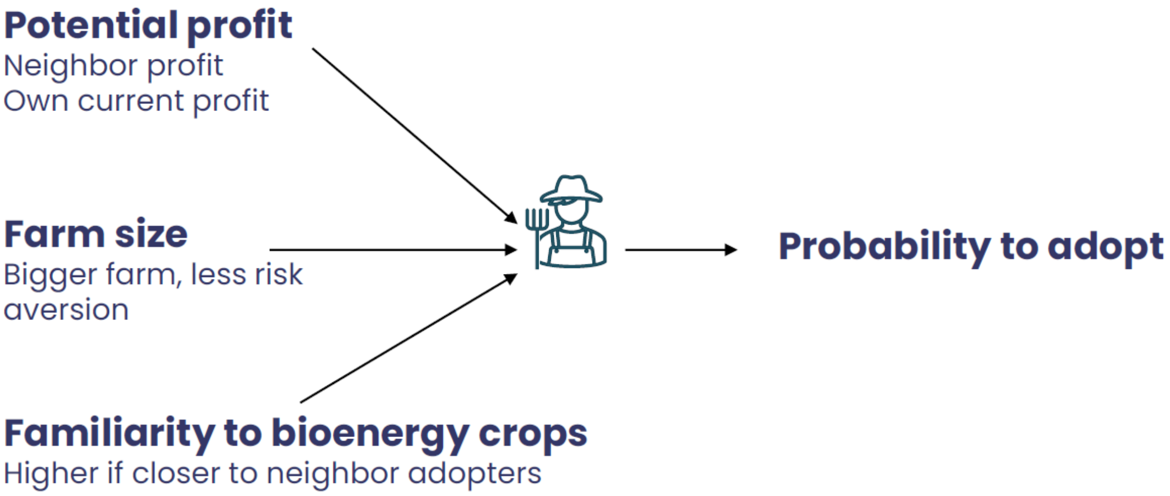

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Initial demonstration farm locations and subsidies

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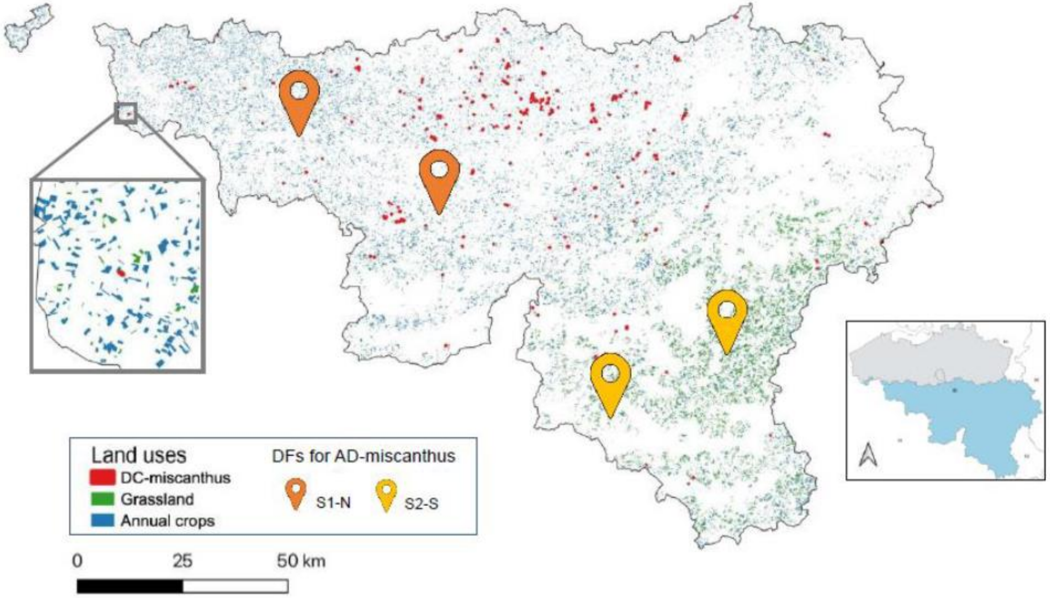
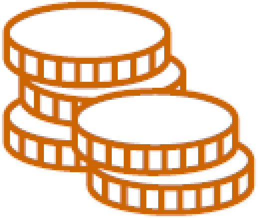
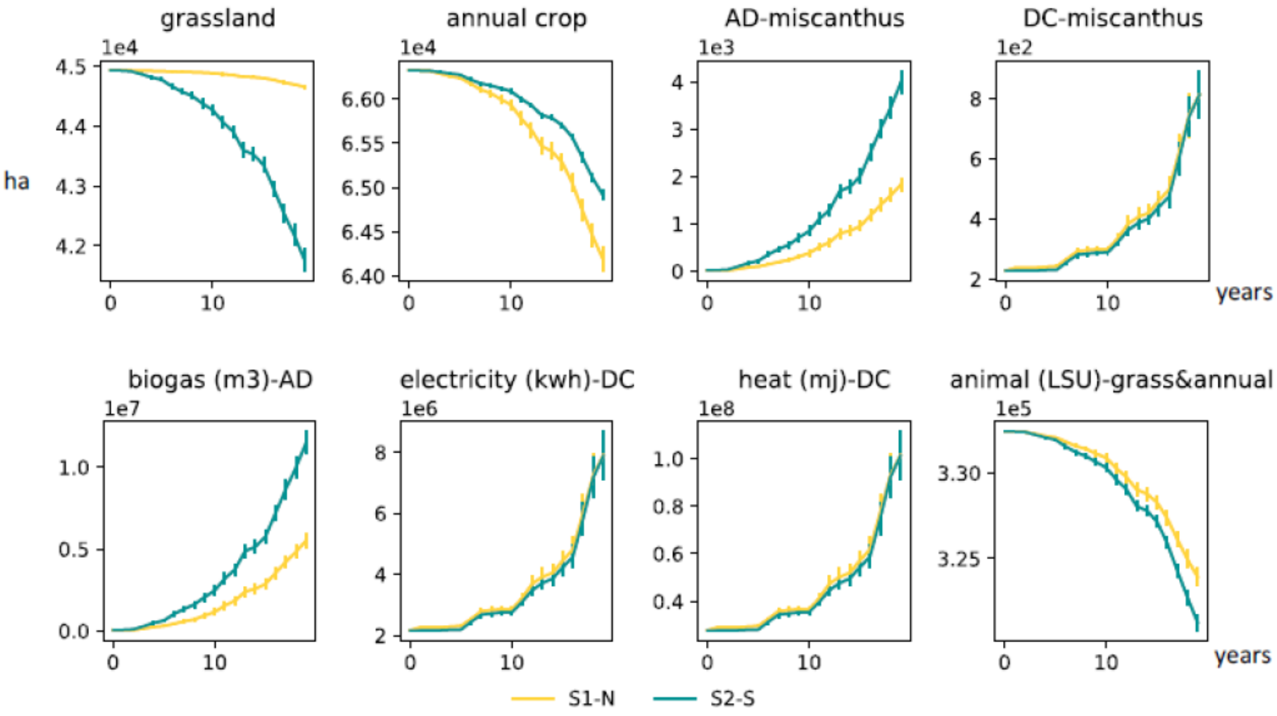




Ding & Achten, 2022

Simulated land use functions



Ding & Achten, 2022

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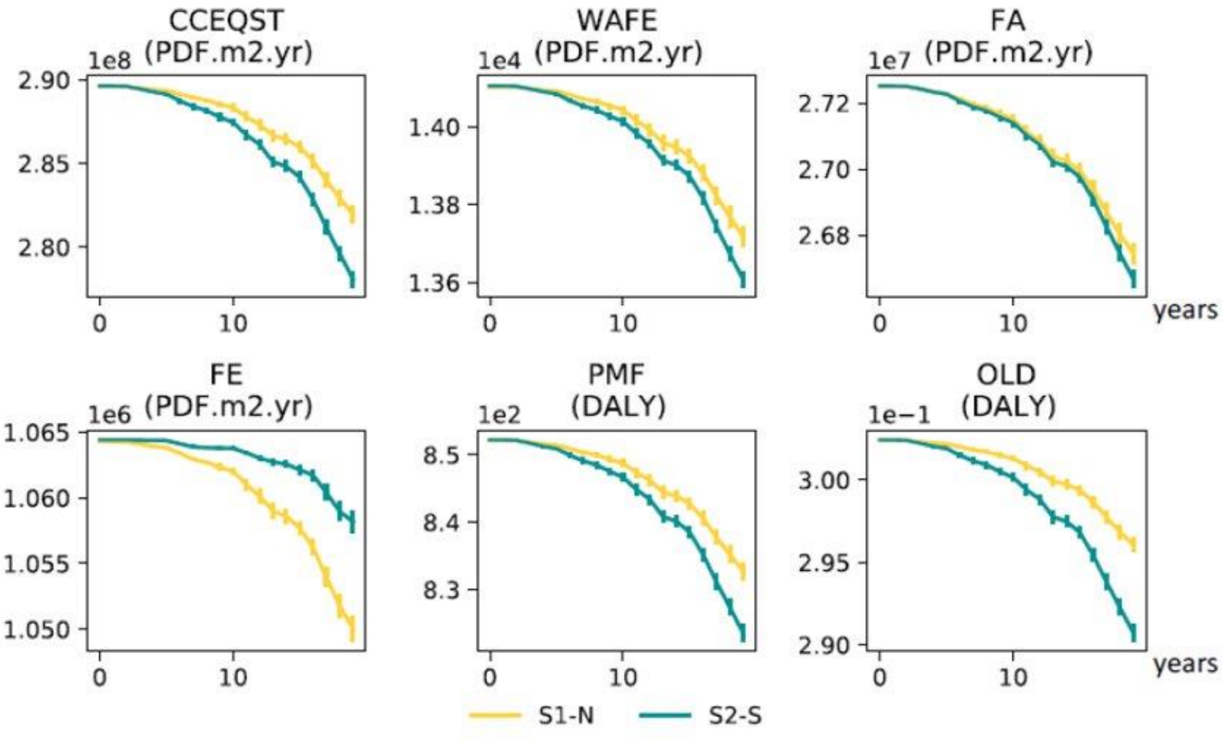
Simulated environmental impacts



Ding & Achten, 2022

Decision support for land use planning

- Where to locate demonstration farms?
- How much incentives need to be considered to reach bioenergy target?
- In how far can neighborhood effects play a role?
- ...

Ding & Achten, 2022

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ABM and energy planning

Simòn Ladino Cano & Maria Anna Hecher

Laboratory on Human-Environment Relations in Urban Systems

FFG

ABM4EnergyTransition

Agent-based simulation of transition scenarios for regional heating and energy transformation.

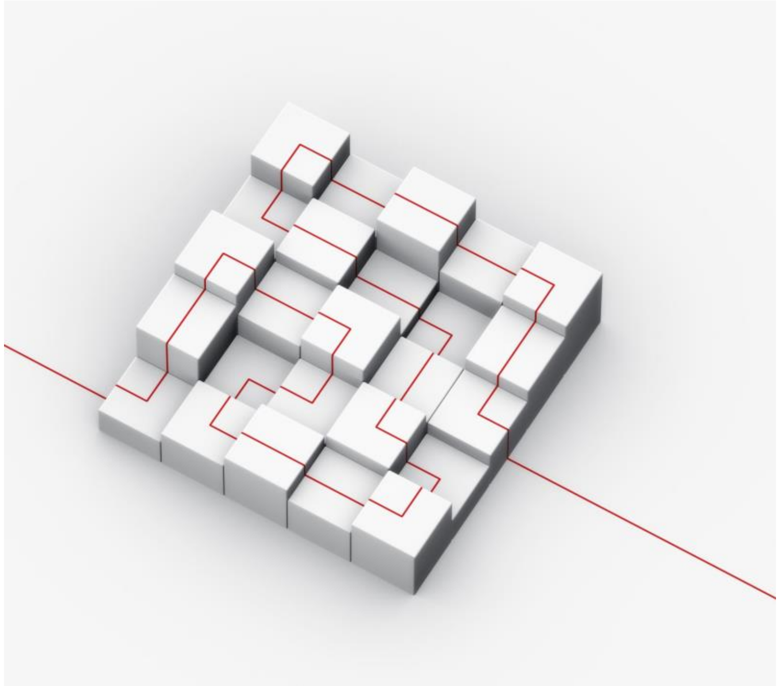
PARIS LODRON UNIVERSITÄT SALZBURG
AEE INTEC
EPFL
MOVING LAYERS
ENERGIE AGENTUR Steiermark
KAPFENBERG

ABM4Energy Transition

Simòn Ladino Cano & Maria Anna Hecher

- **Develop and demonstrate spatial-explicit, empirically grounded agent-based model (ABM)** to simulate urban energy transitions towards 2050 and evaluate impact of policy interventions.

- **Understand factors driving building refurbishment decisions** and explore how to incentivize households to replace carbon-intensive heating systems and to undertake thermal insulation measures.



The Austrian initiative: Spatial Energy Planning for Energy Transition

OBJECTIVE (2018-2024)

Development of all necessary foundations for the implementation of spatial energy planning to enforce a sustainable development of spatial structures while reducing energy demand and minimizing CO_2 emissions.

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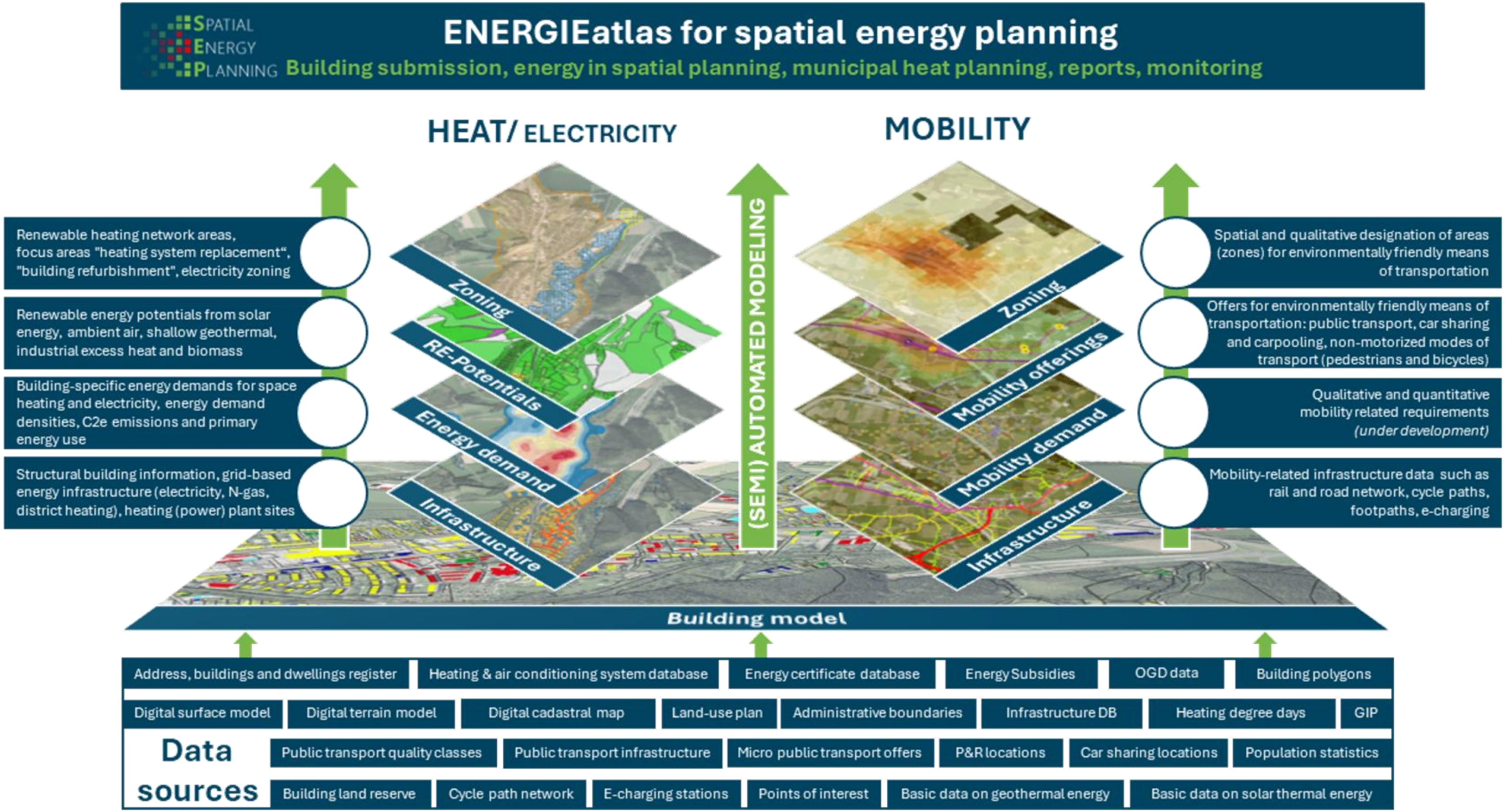
ENERGIEatlas



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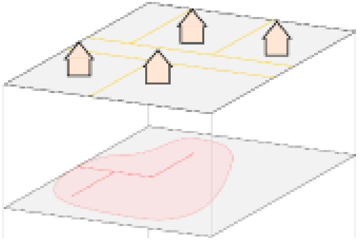
Technical base model

Building renovation and heating system replacement: exclusively based on energy system characteristics, i.e., building age, heat supply infrastructure, renewable energy potentials.

Technical input variables: renovation rates and quality, heating system change rate and preferred heating system technologies etc.

Setup

Model initialization



Building data

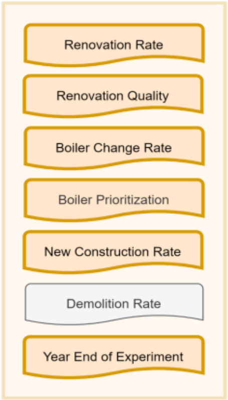
Building characteristics, heating systems, energy demand, etc.

Infrastructure and energy potential data

Energy grids, solar energy potentials, geothermal energy potential, etc.

User input

Input variables



Output

Energy demand by energy carrier, CO_2 emissions, etc.

Use cases

City planners, energy service providers and energy experts

- Energy transition scenarios & sensitivity
- Assessment of energy policy measures
- Municipal heat planning
- Zoning

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Behavioral model extension

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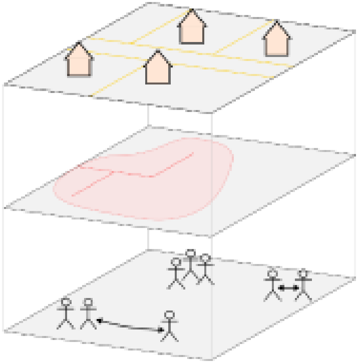
Building renovation and heating system replacement: additionally influenced by agents' behavior, i.e., attitude, social norm and perceived context.

Input variables: interventions such as regulations, financial incentives, and information campaigns shape this behavior and, consequently, the simulation results.

Setup

Model initialization



Building data

Building characteristics, heating systems, energy demand, etc.

Infrastructure and energy potential data

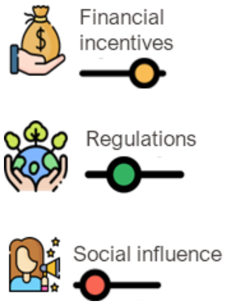
Energy grids, solar energy potentials, geothermal energy potential, etc.

Agents' decisions

Refurbishment behavior defined through threshold related to attitude, social norm, and perceived context for refurbishment

User input

Input variables



Output

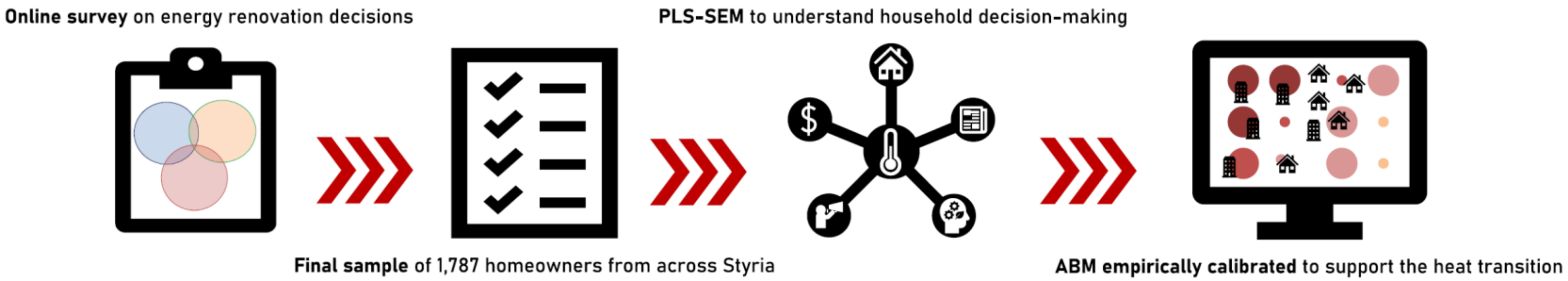
Energy demand by energy carrier, CO_2 emissions, etc.

Use cases

City planners, energy service providers and energy experts

- Energy transition scenarios & sensitivity
- Assessment of energy policy measures
- Municipal heat planning
- Zoning

Agents' decisions for refurbishment and heating system replacements



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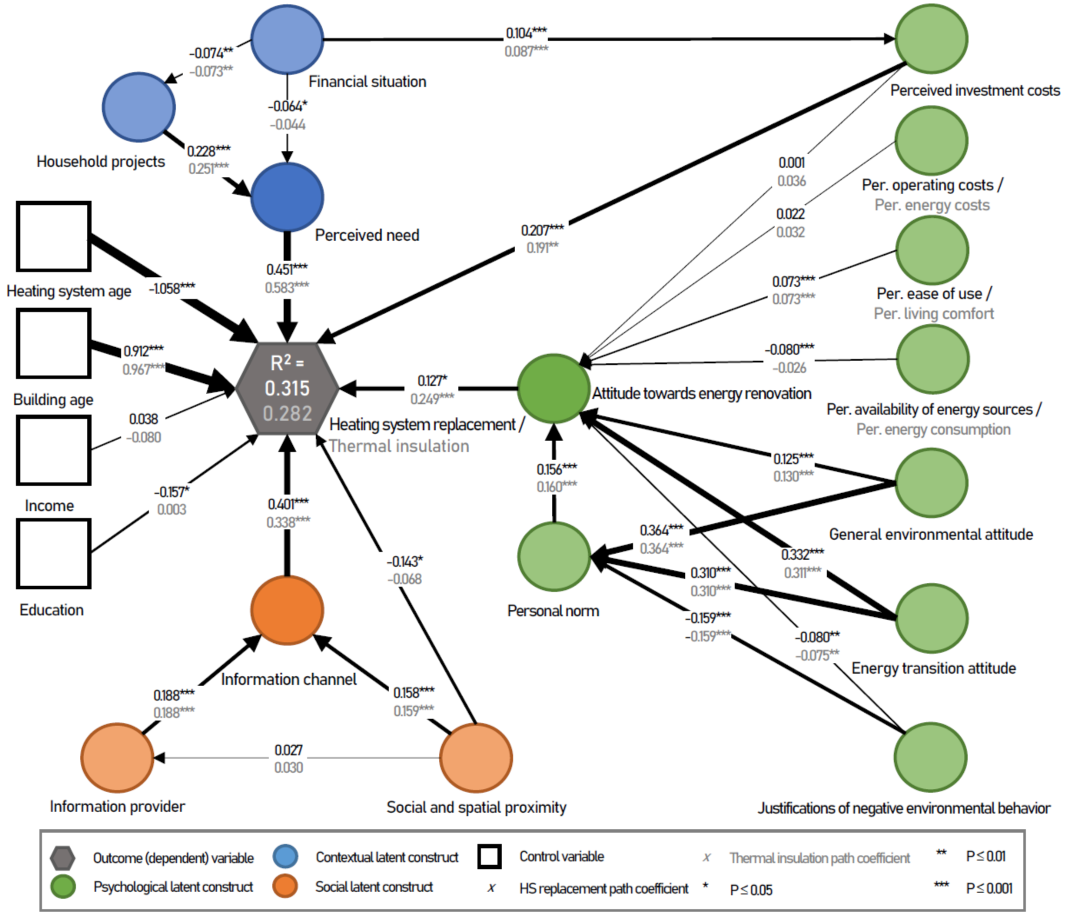
Context, attitude and information exchange matters

Sample of 1,787 homeowners in Styria, Austria (June - July 2023)



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Behavioral model processes

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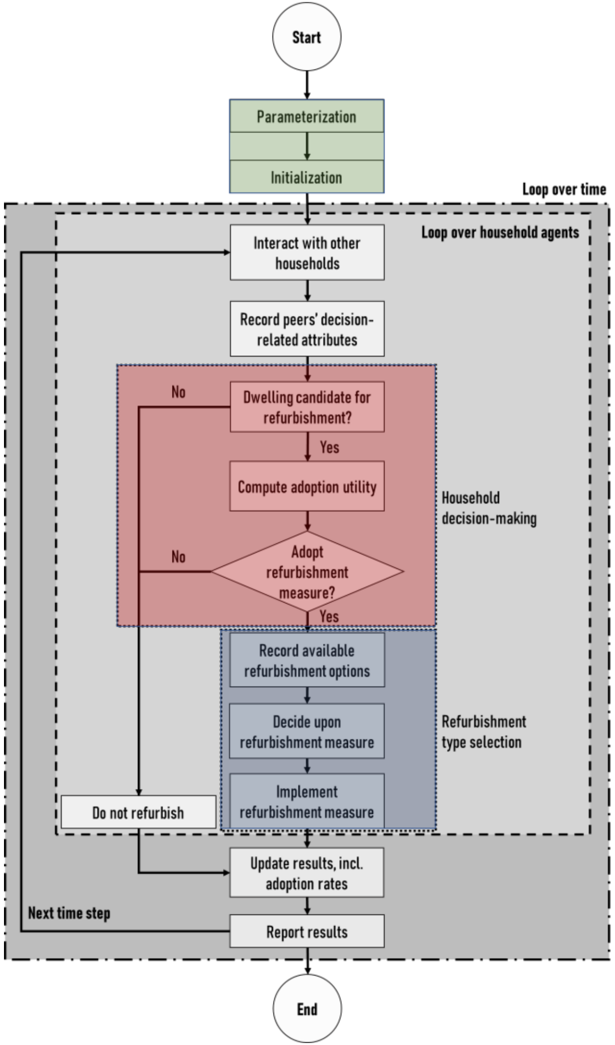

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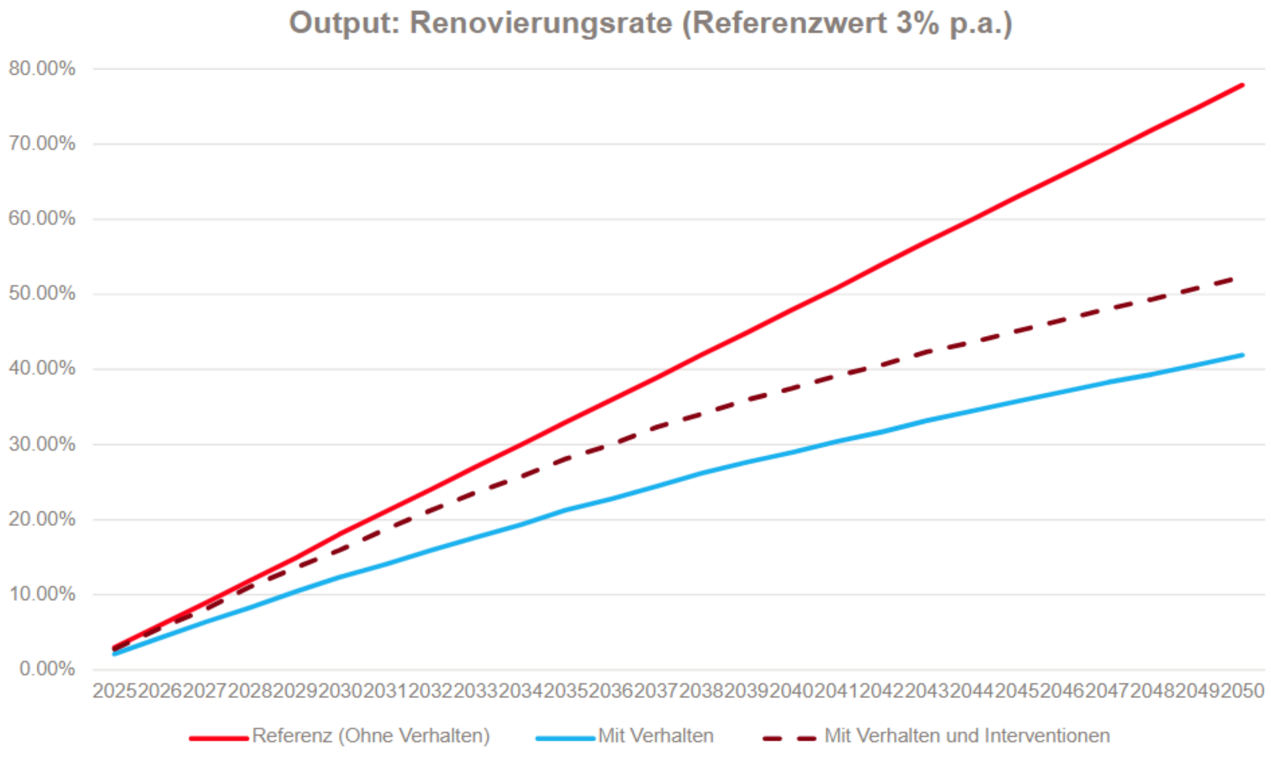
Renovation rate: Technical vs. behavioral model



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WebGIS Demo

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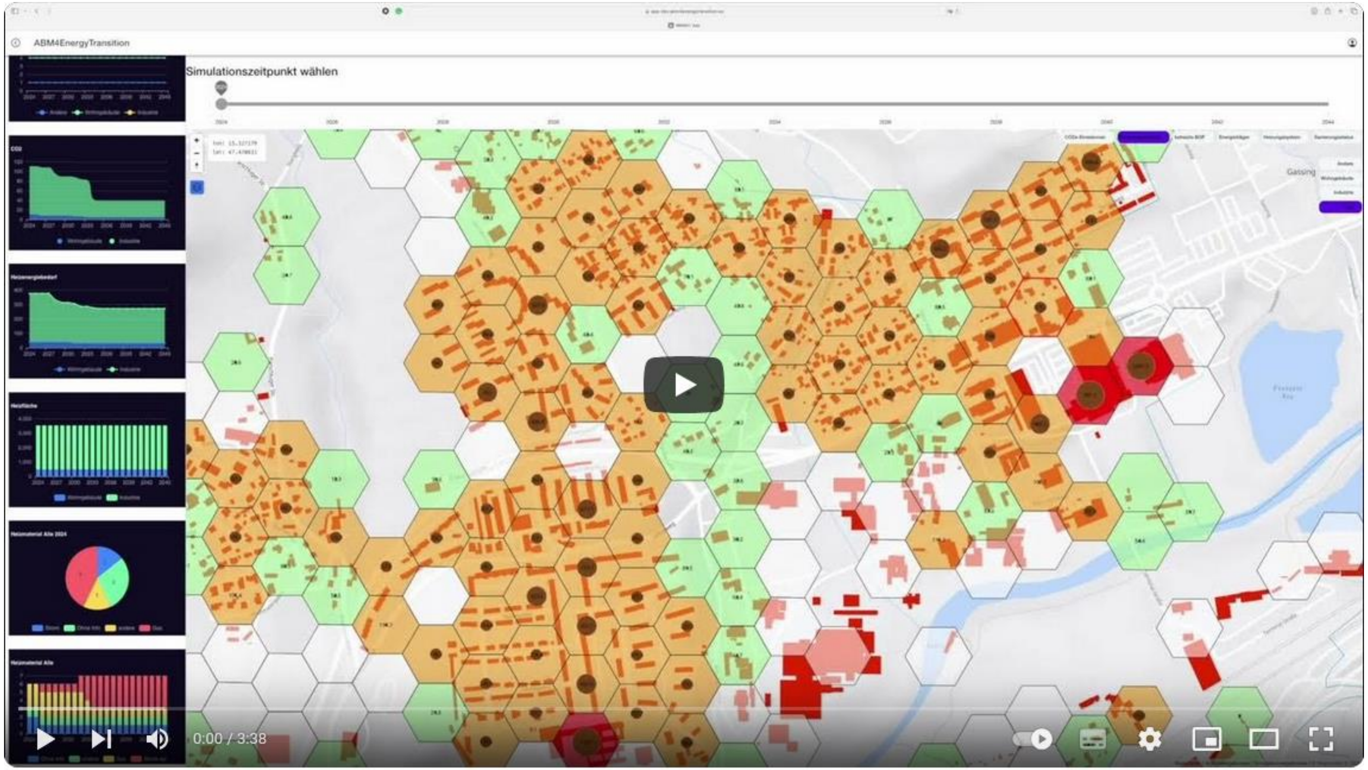

Smart Energy Systems Conference 2024 (SESAAU) in Aalborg, Denmark

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WebGIS Demo

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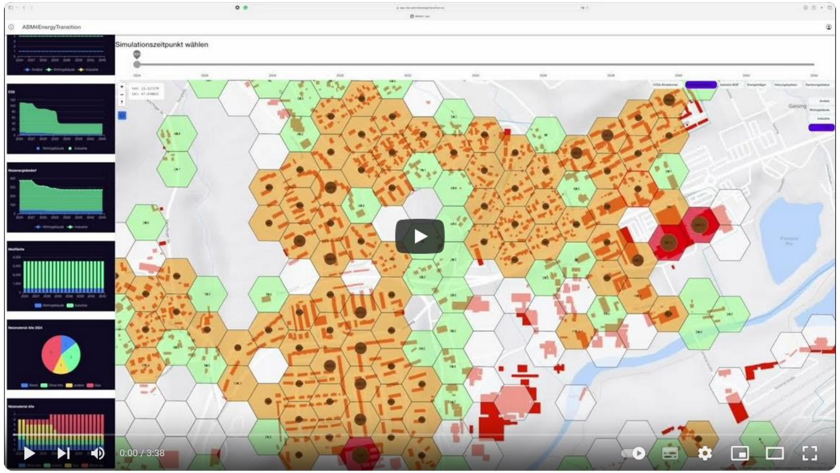

Application

https://app.abm4energytransition.eu/login

Email

guest@abm4energytransition.eu

Password

Willkommen2024!

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