

**ENV 501 / GR A3 30**

# **Material Flow Analysis and resource management**

Prof. Dr. Claudia R. Binder [claudia.binder@epfl.ch](mailto:claudia.binder@epfl.ch)

Dr. Francisco Xavier Felix Martin Del Campo [francisco.felixmartindelcampo@epfl.ch](mailto:francisco.felixmartindelcampo@epfl.ch)

Exercices Teacher Assistant Jaír Campfens [jair.campfens@epfl.ch](mailto:jair.campfens@epfl.ch)

Exercices Teacher Assistant Léonard Léchet [leonard.lechet@epfl.ch](mailto:leonard.lechet@epfl.ch)

Student Assistant Alicia Pérez Domouso [alicia.perezdomouso@epfl.ch](mailto:alicia.perezdomouso@epfl.ch)

- 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

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 11	Introduction to the course and general concepts	All	Exercise	Project
W2 - Sep 18	EW – MFA and EW – MFA in the Swiss context	External Guest – Florian Kohler	Exercise	Project
W3 – Sep 25	Examples of EW – MFA. Scaling EW-MFA to Cantons	FMC	Exercise	Project
W4 - Oct 02	Urban Metabolism and Circular Economy	FMC	Exercise	Project

Block II:  
MFA  
regional /  
urban

W5 - Oct 09	MFA method and the Stock-Flows-Service Nexus	CRB	Exercise	Project
W6 - Oct 16	Dynamic MFA	CRB	Exercise	Project
Oct 23	Autumn break			
W7 - Oct 30	Applications of MFA – case study	External Guest – Guillaume Massard	Exercise	Project
W8 - Nov 06	Input-Output Analysis and Material Flow Cost Accounting	External Guest – Vincent Moreau	Exercise	Project
W9 - Nov 13	Spatial MFA	FMC	Exercise	Project
W10 - Nov 20	Combined approaches: MFA + LCA; MFA + sociodemographics.	AS & FMC	Exercise	Project

Block III:  
Social  
sciences  
and  
public  
policy

W11 - Nov 27	Combined approaches: MFA + surveys; Quasi-dynamic MFA	GF & FMC	Exercise	Project
W12 - Dec 04	Social metabolism	CRB	Past exam	Project
W13 - Dec 11	Agent-based model	CRB, FMC, HL, MAH	Project	Project
W14 - Dec 18	Group Project Presentation	All	Project	Project



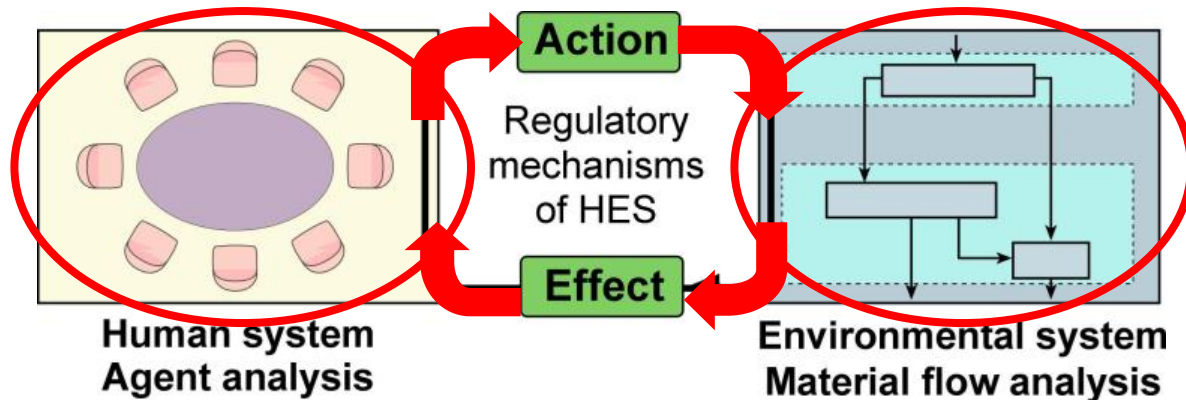
# From Material Flow Analysis to Material Flow Management

# MFA for policy-making: Material Flow Management

**Policy makers have rarely included MFA results in their decision-making at a regional level:**

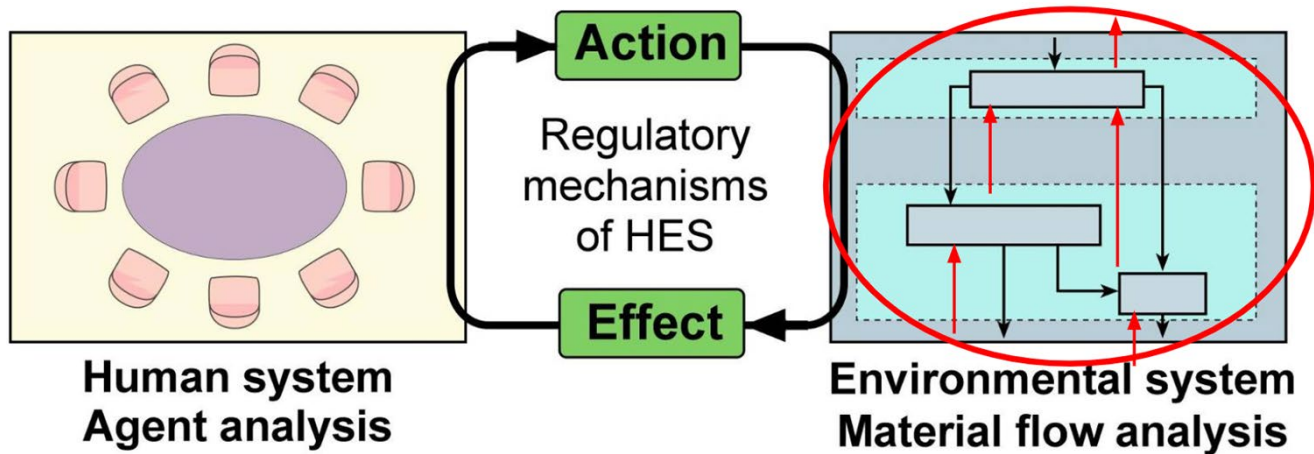
- there is a need to improve the structure for interpreting MFA results, i.e. the goals of material management are not always clearly defined.
- the number of stakeholders involved increases with increasing levels of aggregation and it becomes unclear who is responsible for taking action.
- the uncertainty of the data increases.

# Linking MFA results with the social system [1]



## Key questions:

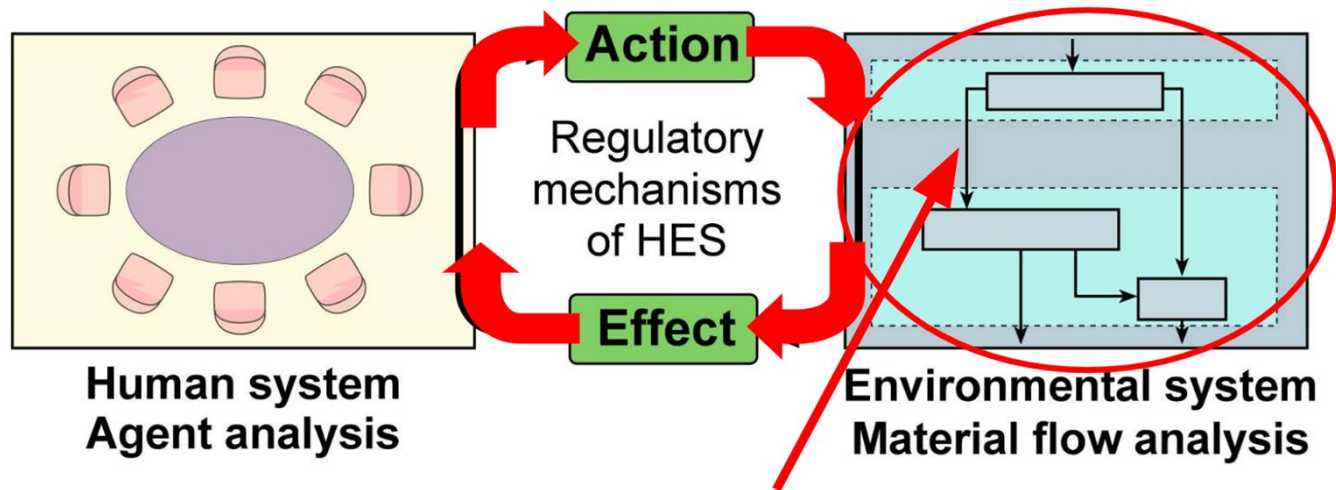
- What are the key problems in the environmental system?
- Which actions of humans affect or are related to these environmental problems?
- Which parameters do drive these actions?
- How can we monitor the effect of these actions?



**What are the economic flows associated with the material flows?**

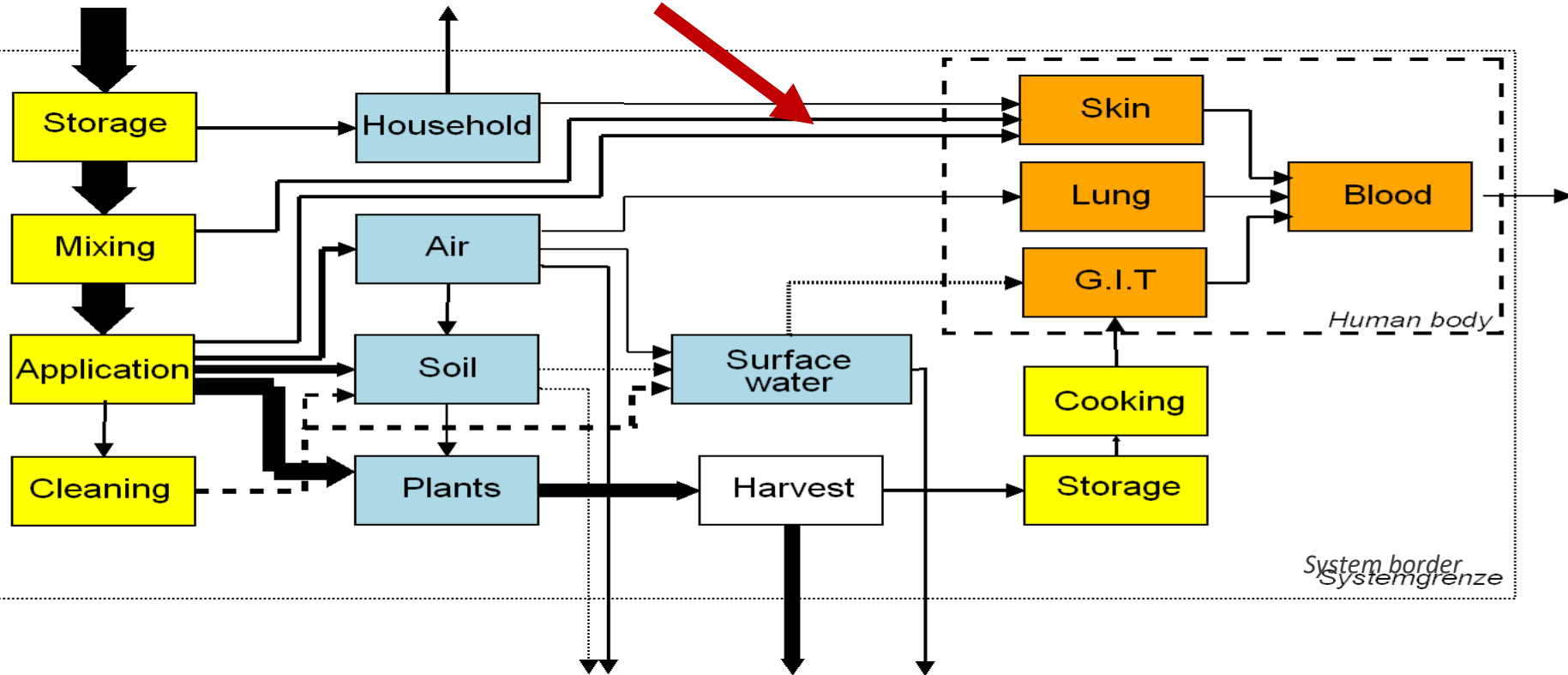
⇒ *Input/Output Analysis*

# Linking MFA results with the social system [3]

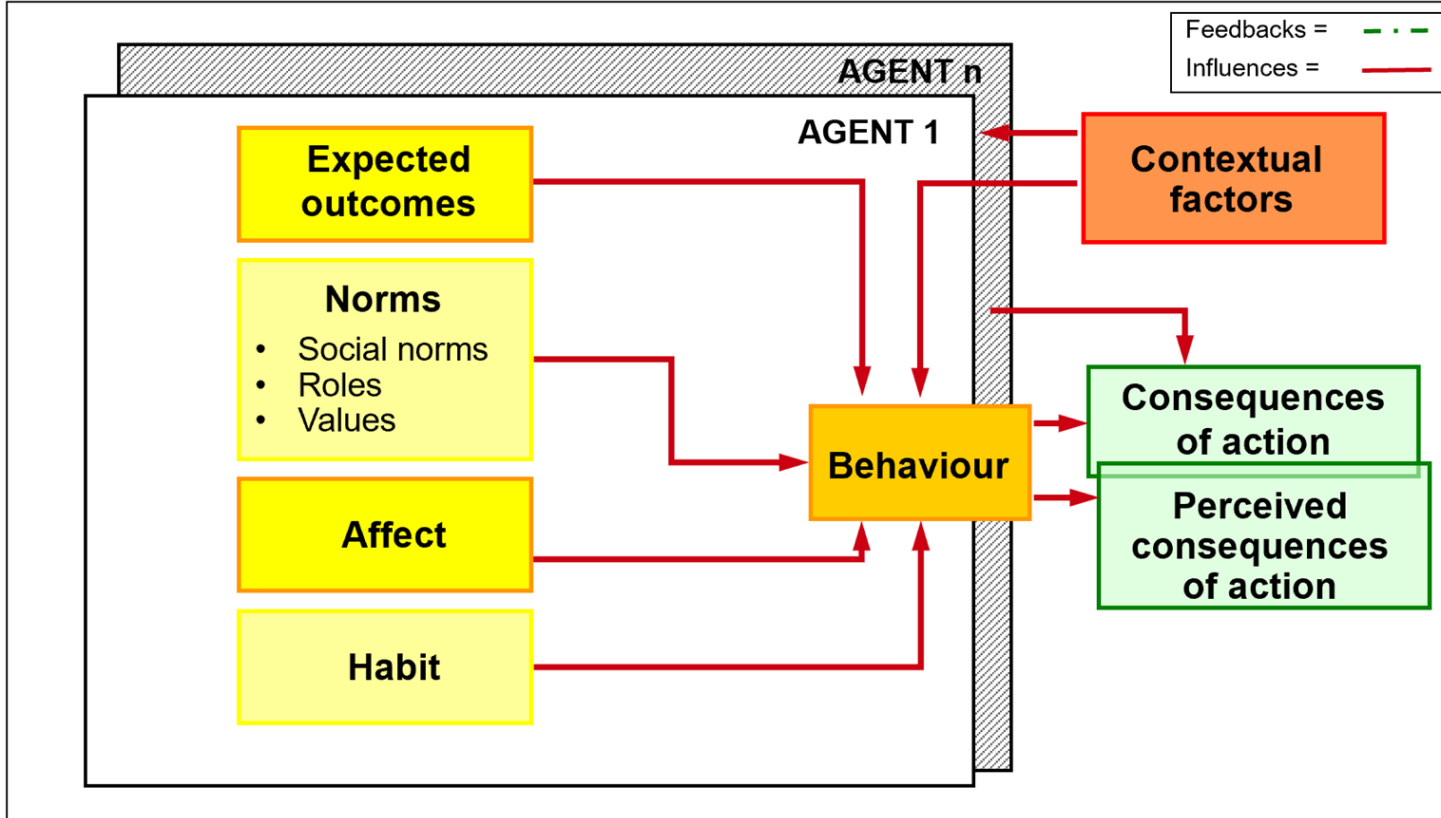


Which parameters affect the decision-making process relevant for specific material flows?

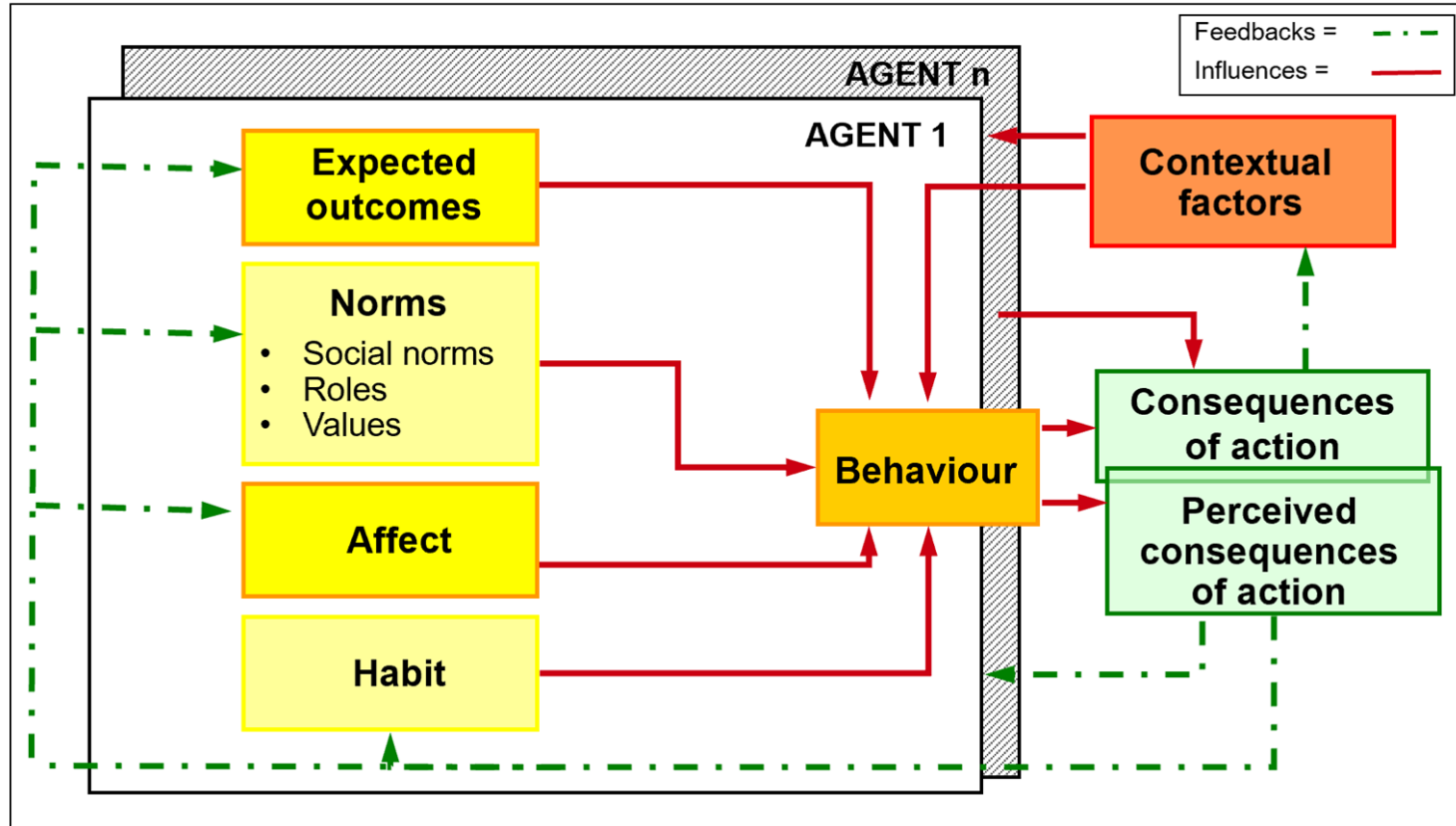
⇒ *Statistics / decision-making models / econometrics*



# The Integrated Agent-Centred Framework



# The Integrated Agent-Centred Framework



# Behavioral model: Use of protective equipment (PPE)

Variable	Marginal effect
Compliance prescriptive norm (Pesticide label) **	4.855
<b>Past health effects ***</b>	<b>3.116</b>
<b>Descriptive norm ***</b>	<b>2.631</b>
Age**	0.964
Work organization **	0.053
Age * Work organisation**	1.061

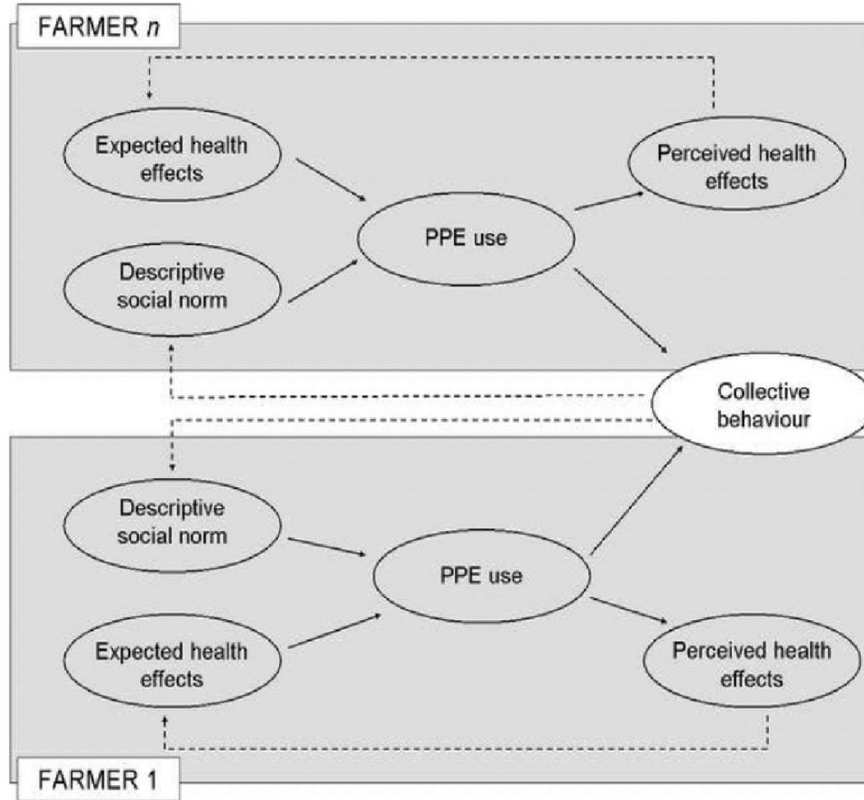
\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; correct predictions: 70%

# Behavioral model: Use of protective equipment (PPE)

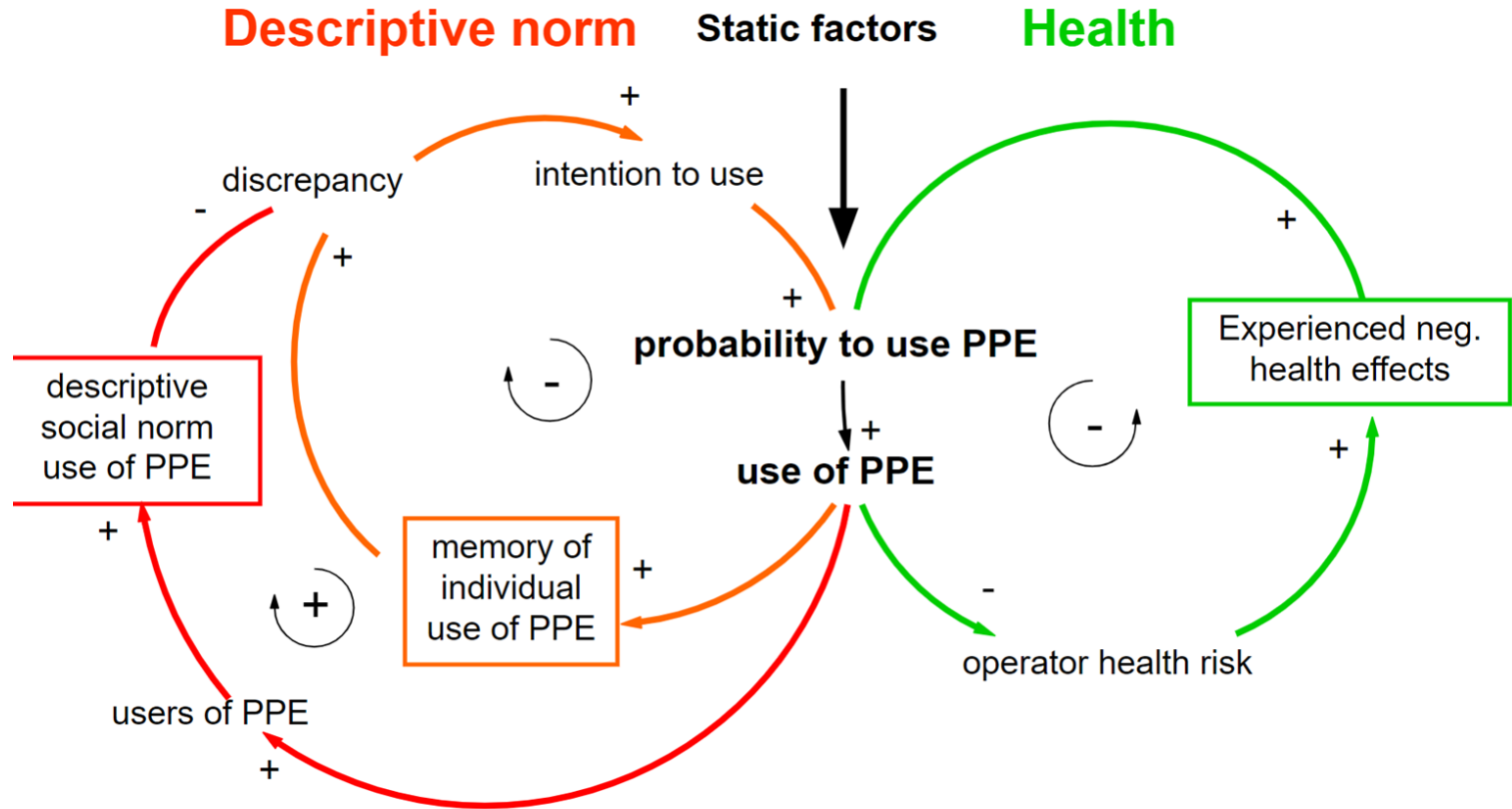
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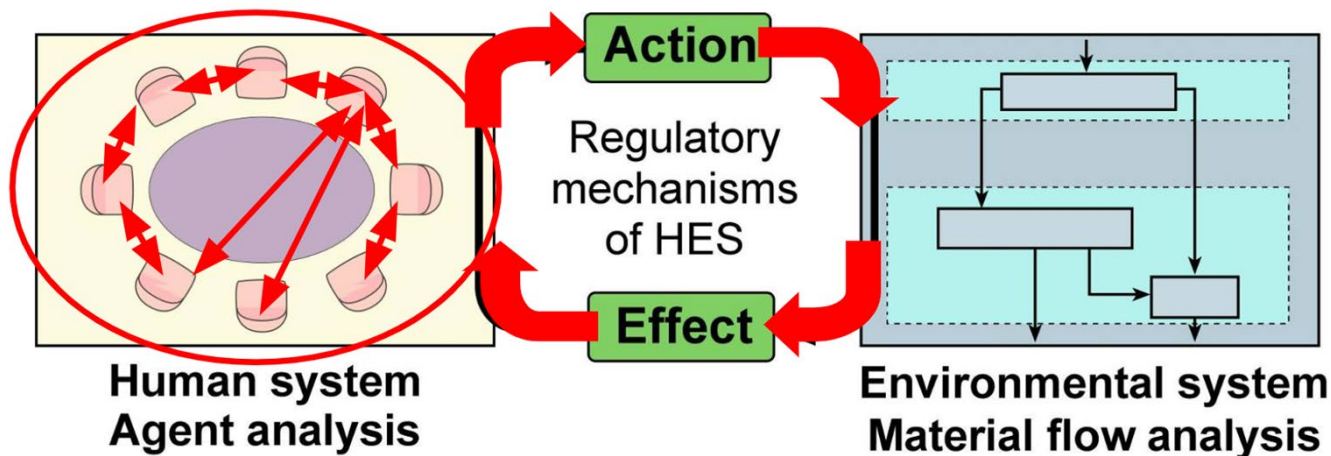
\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; correct predictions: 70%

# PPE simulation (simpl.)



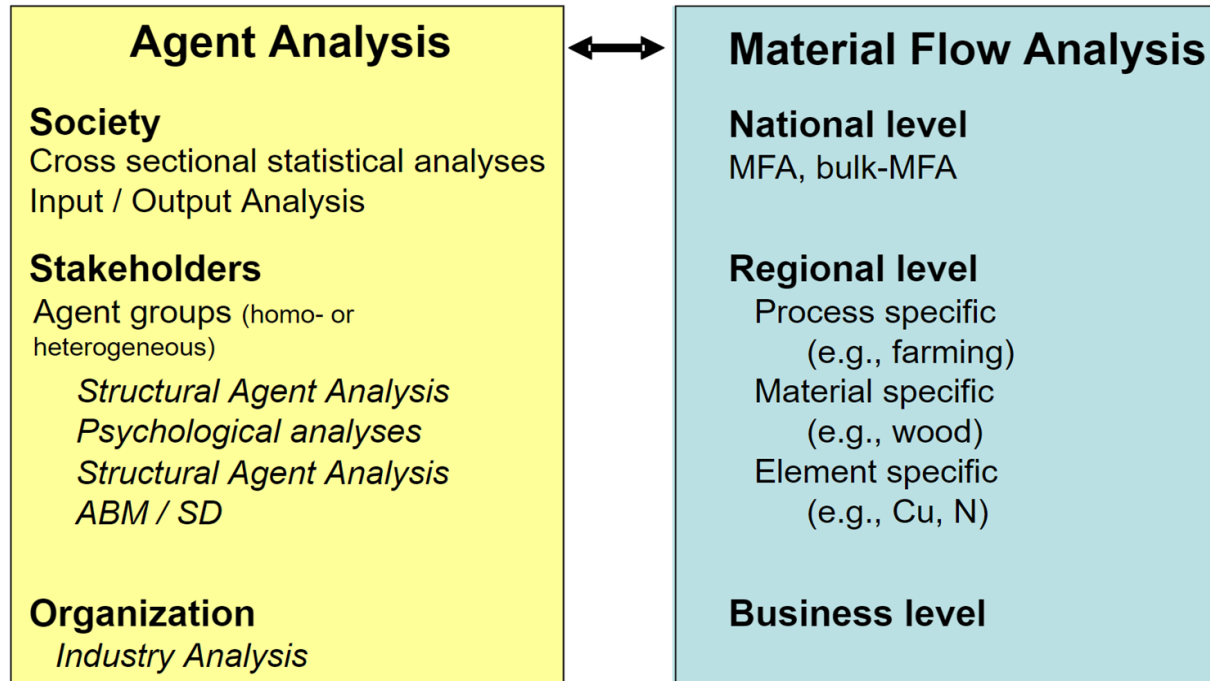
# PPE simulation: Causal loops (simpl.)





What hinders / promotes the implementation of sustainable measures?  
 What is the role of interaction of stakeholders?  
 ⇒ *Agent Analysis / Modeling techniques (SD, ABM)*

# Steering MFA systems: The necessity of analyzing actors



# Conclusion [1]

## Linking MFA with social science methods can significantly support:

- ✦ the development of adequate measures considering human behavior.
- ✦ the analysis if implementation of best policies is possible.

## MFA can bridge to other disciplines through:

- ✦ a specific flow (behavior affecting a specific flow).
- ✦ aiming at changing the system (behaviors of several actors affecting the stocks and flows).

# Conclusion [2]

**It is crucial to consider scale and agent composition when selecting the social science method to be used:**

- ✦ Homogenous agent group  $\Rightarrow$  statistical, econometric analysis, SD
- ✦ Heterogeneous agent groups  $\Rightarrow$  interaction analysis ABM, SD  
(quantitative approaches)

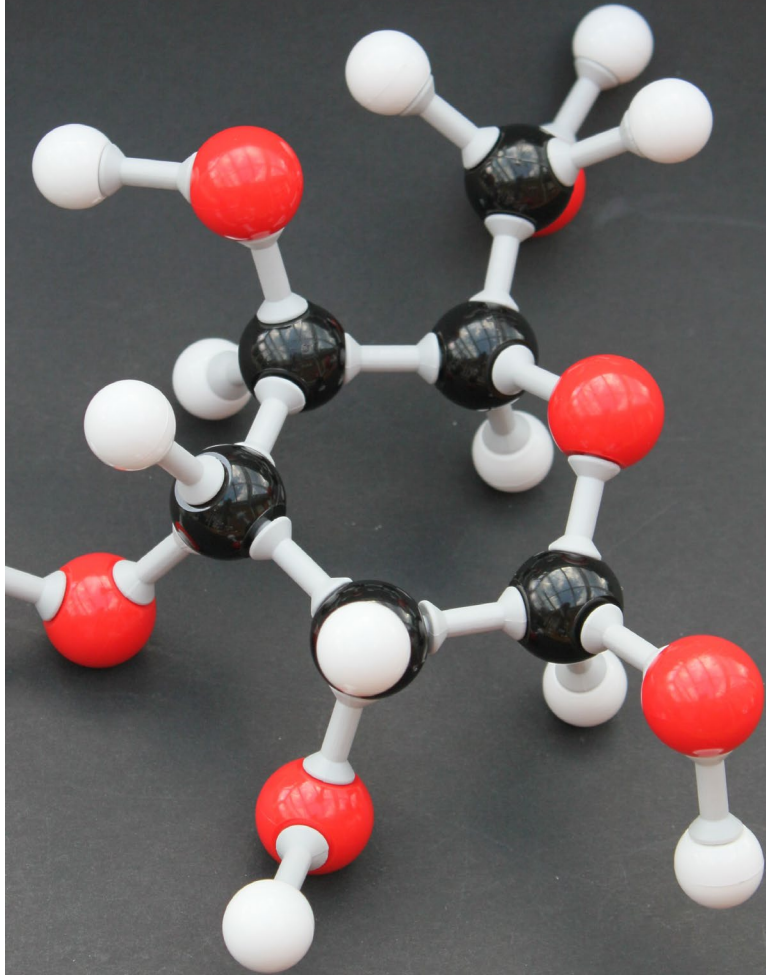
(qualitative approach)

Structural Agent Analysis

- Understand the key characteristics of Agent-Based Models (ABM) and their application fields
- Recognize the purpose of ABMs in Industrial Ecology and its added value

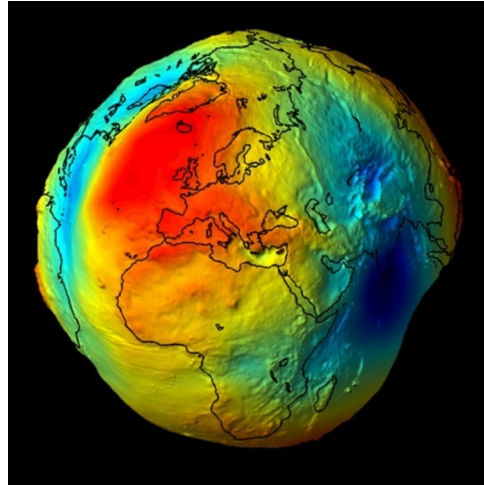
# Agent-Based Modelling and applications fields





# Models

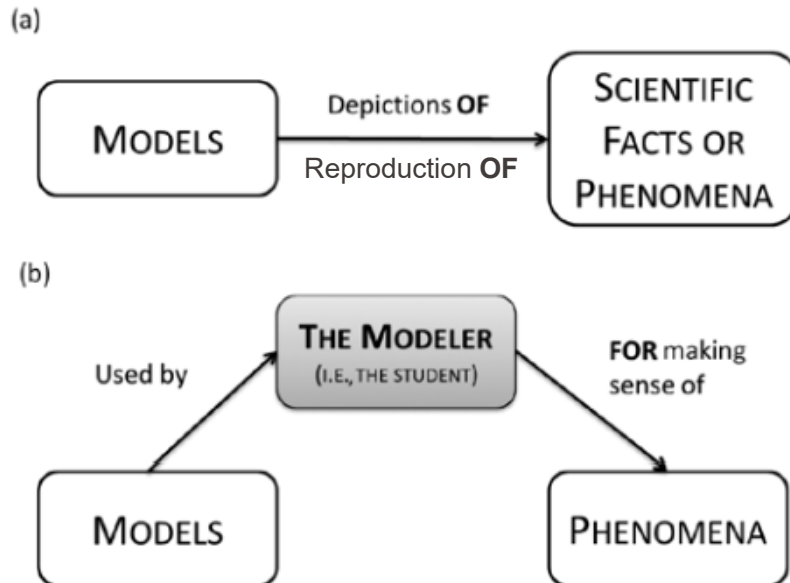
A model is a simplified representation of reality.



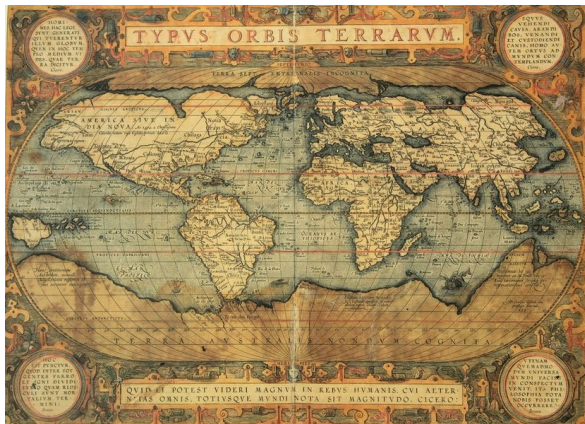
*“(...) all models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind.”*

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

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

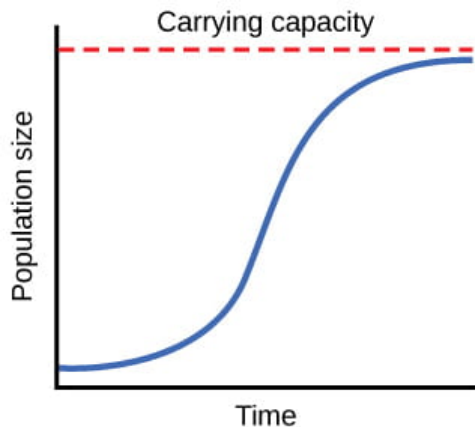


## Physical models



Source: Atlas Obscura

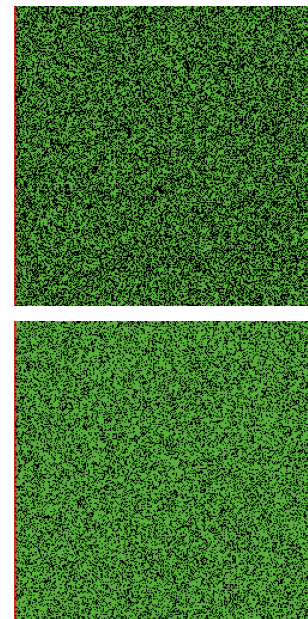
## Mathematical models



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

Source: OpenStax Biology

## Computational models

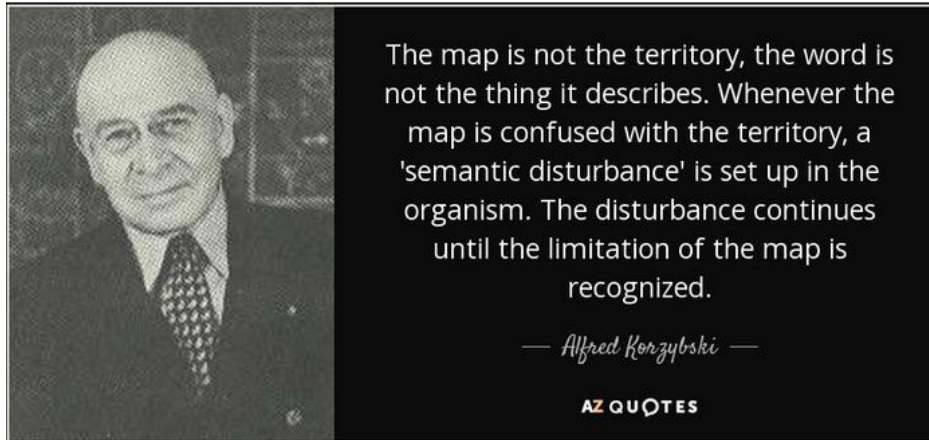


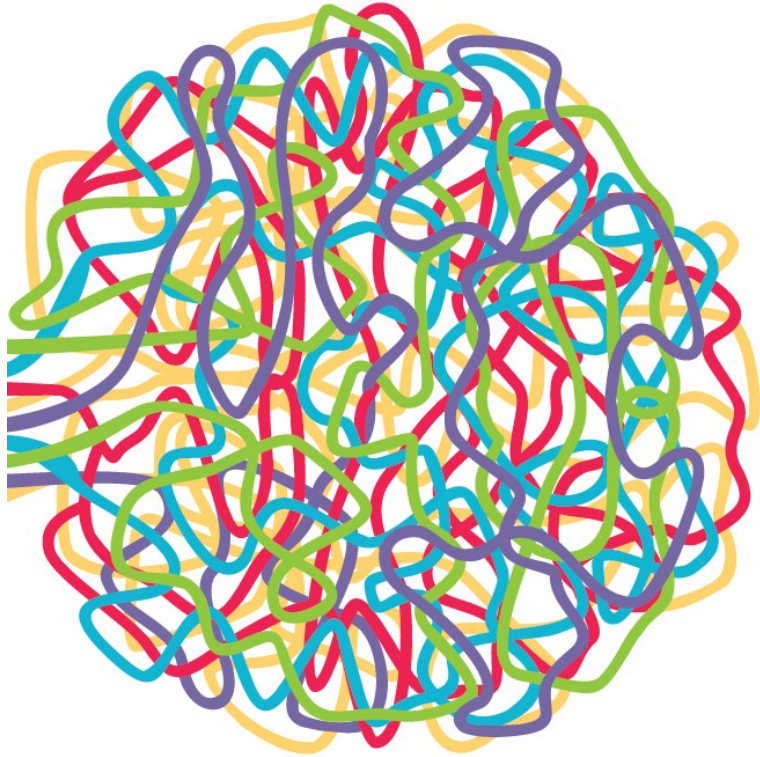
Source: NetLogo Models Library

Bonabeau (2002), Wilensky & Rand (2015)

# What a model is NOT

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





# Complex systems

# What is a complex system?

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

# Core features of complex systems

**1. Nonlinearity:** Small changes can lead to large, unpredictable effects.

## Feedback loops:

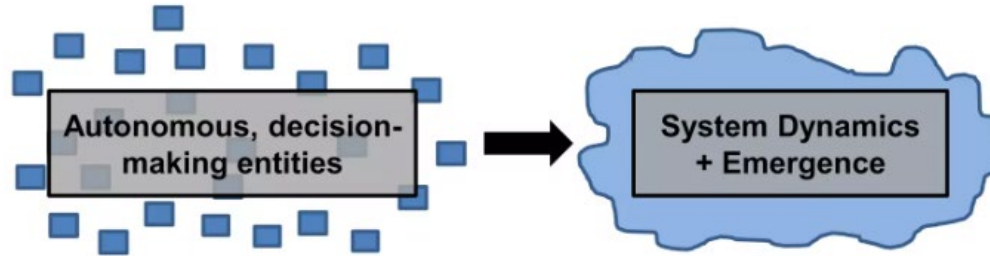
- Positive (reinforcing) feedback: Amplifies change.
- Negative (stabilizing) feedback: Stabilizes the system.

**2. Emergence:** Macro-level patterns arise spontaneously from micro-level interactions.

**3. Adaptation:** Systems change based on internal/external influences and past experience.

**4. Robustness:** Order is stable under perturbations of the system, given its distributed nature and lack of central control.

# Complex Systems



*"Whole is greater than the sum of it's parts"*



Source: Colossal



Source: Dribble



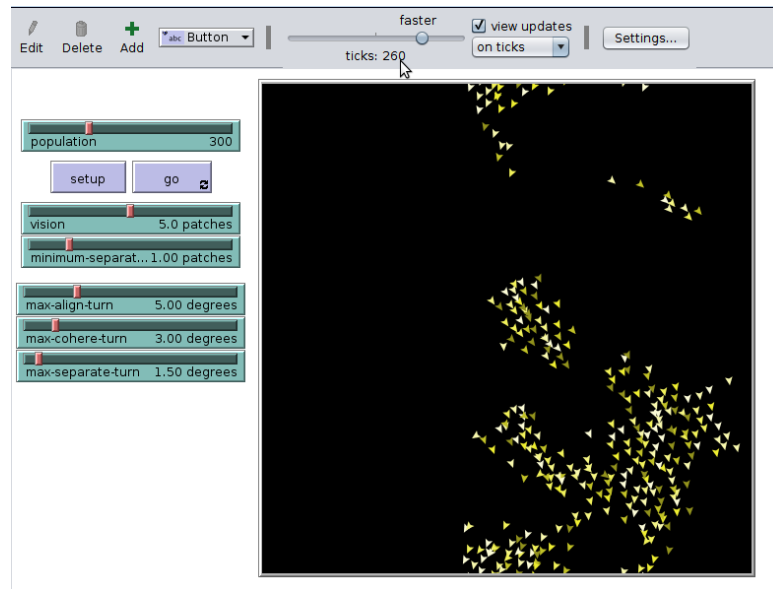
Source: Dribble



# 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

# Key characteristics of ABM

Components:

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

Features:

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



Source: Ramadhah, Galbiati, & Soramaki (2021)

# Why use ABM?

- **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.

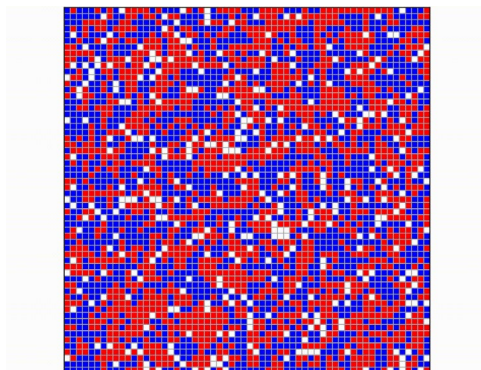
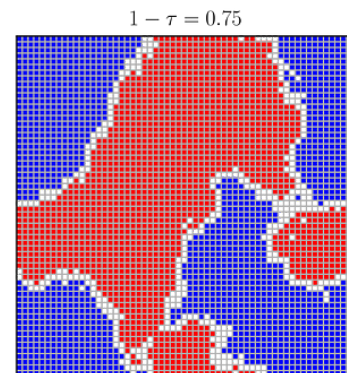
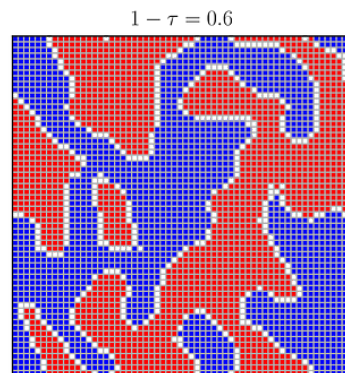
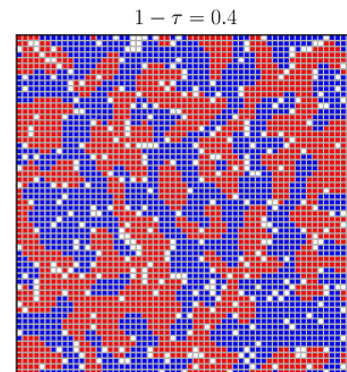
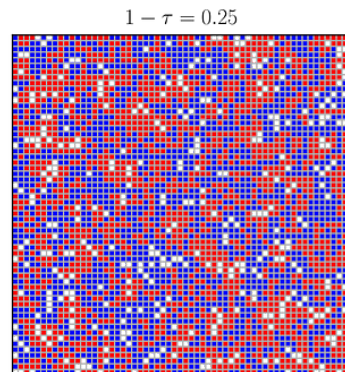
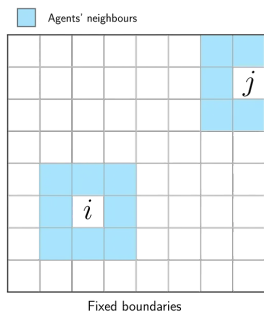
Criteria	Equation-based Modeling	Agent-based Modeling
Theoretical foundation	High, theory-driven	Low, data-driven
Direction of approach	Top-down, aggregate	Bottom-up, disaggregate
Expression	Mathematical equations	Programming language
Techniques	Statistics	Neural networks, big data analytics
Compute 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)

# Schelling's segregation model (1978)

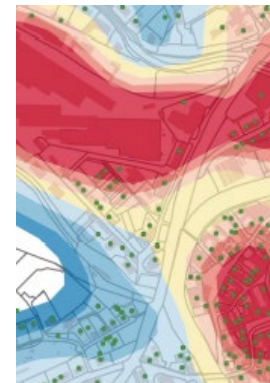
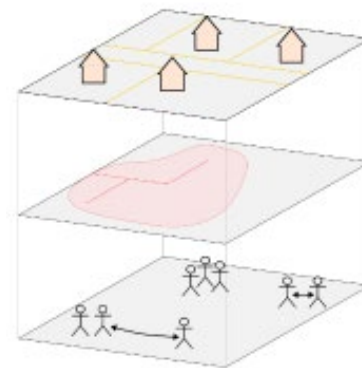
- Even weak local preferences can lead to segregation at global level emerging from network of individual micro interactions



Mingarelli (2021)

Wilensky &amp; Rand (2015)

- **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



Weinberger et al., 2025

# ABMs have limitations



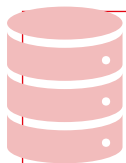
## High Computational Cost.

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

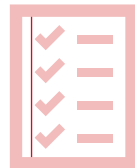


## Dependency on Assumptions.

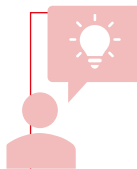
The accuracy of an ABM relies heavily on the validity of assumptions about agent behavior and interactions.



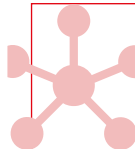
**Data Requirements.** High-quality data is often needed to define agent characteristics and interactions.



**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.

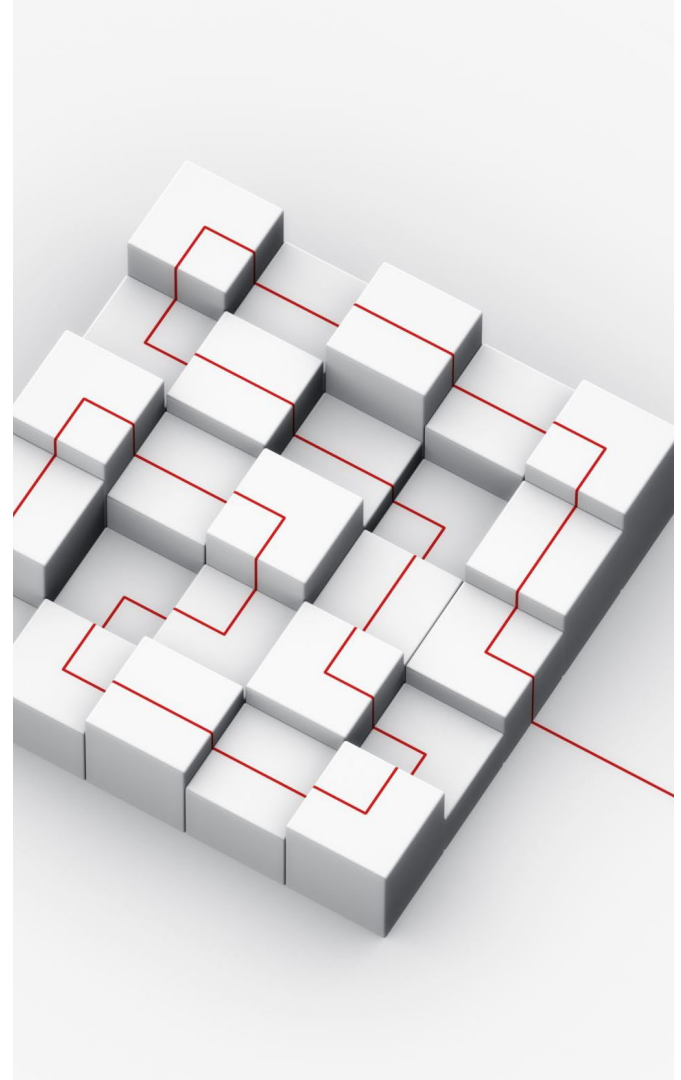
# Summary

- ABM is an excellent tool for modelling phenomena where individual behavior is central to defining system characteristics
- ABM can be used for prediction and examination of expected and unexpected behaviors
- Applicable to range of different domains
- Careful agent design and validation is crucial!
- Range of open-source platforms are available



# ABM and Energy Planning

- Spatial-explicit, empirically grounded agent-based model (ABM) to simulate urban transitions
- Tool to evaluate impact of policy interventions to support cities in energy planning
- Integration of human behavior in building models
- Science-policy interface



- Climate neutrality by 2024
- Renovation rate needs to be doubled
- Residential sector 1.7% - 3%
- Renewable Heating Act 2023

 Federal Ministry  
Republic of Austria  
Sustainability and Tourism

## Long-Term Strategy 2050 - Austria

Period through to 2050

pursuant to Regulation (EU) 2018/1999 of the European Parliament and of the Council on the Governance of the Energy Union and Climate Action

as per Decision 1/CP.21, paragraph 35 in accordance with Article 4, paragraph 19 of the Paris Agreement

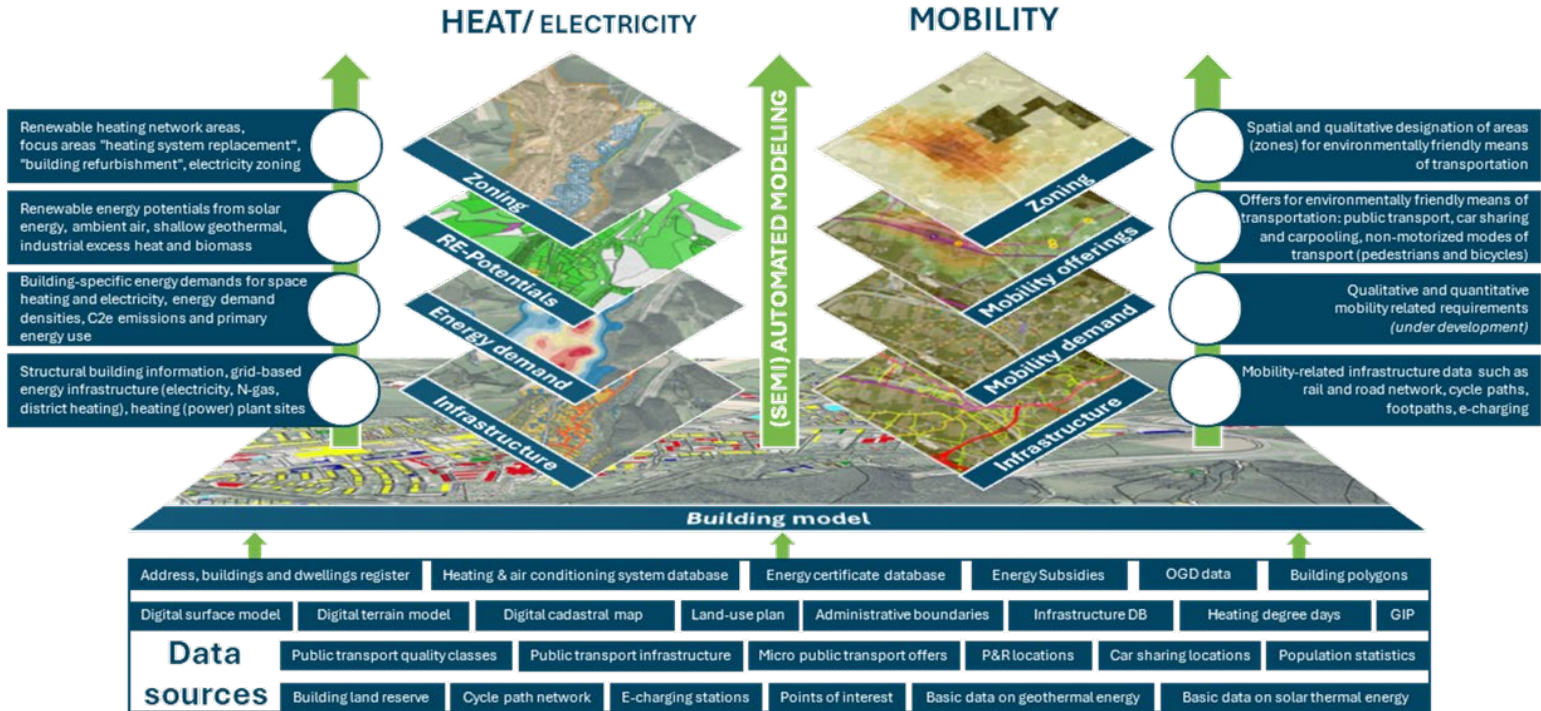
# The Austrian initiative: Spatial Energy Planning for Energy Transition

## OBJECTIVE (2018-2024)

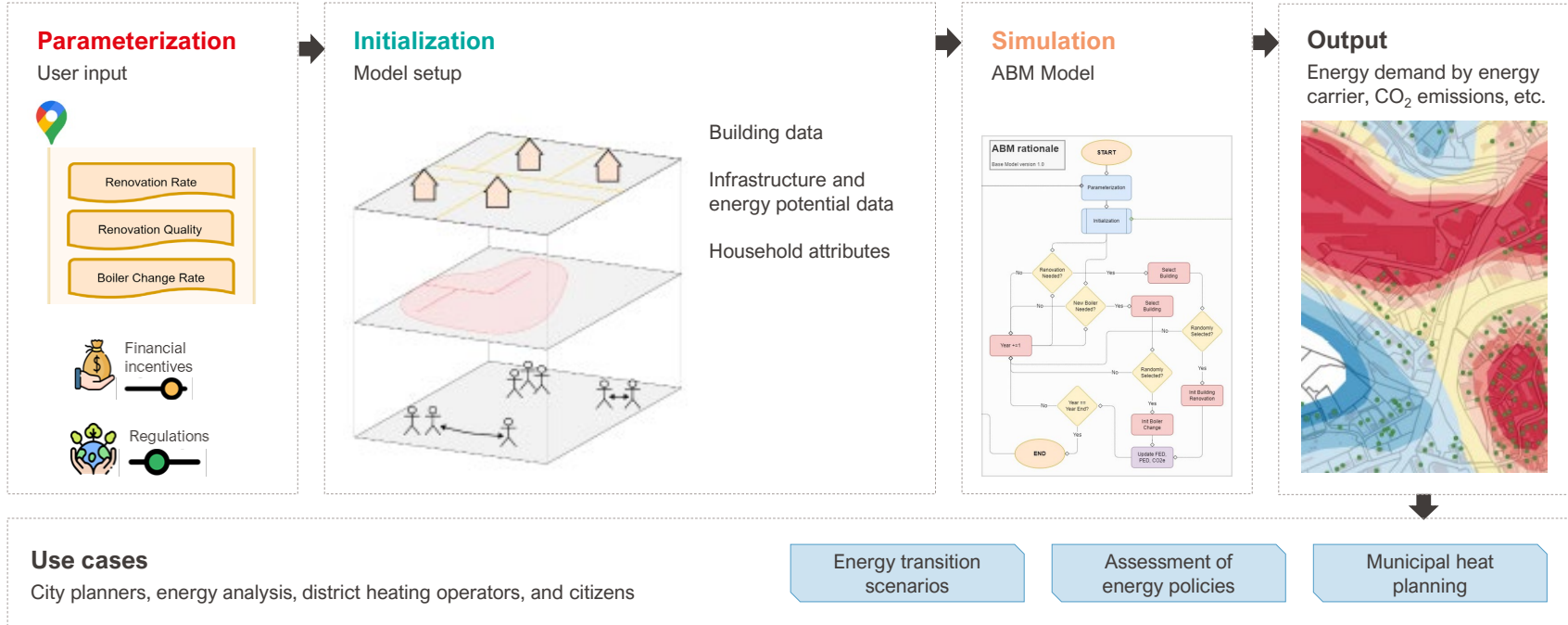
Development of all necessary foundations for the implementation of spatial energy planning to enforce a sustainable development of spatial structures while reducing energy demand and minimizing CO2 emissions.



**ENERGIEatlas for spatial energy planning**  
 Building submission, energy in spatial planning, municipal heat planning, reports, monitoring



# ABM4Energy Transition approach

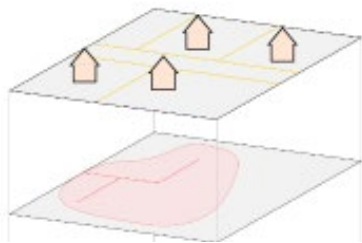


**Building renovation and heating system replacement:** exclusively based on energy system characteristics, i.e., building age, heat supply infrastructure, renewable energy potentials.

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

## Setup

Model initialization



## Building data

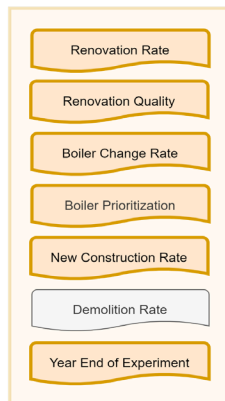
Building characteristics, heating systems, energy demand, etc.

## Infrastructure and energy potential data

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

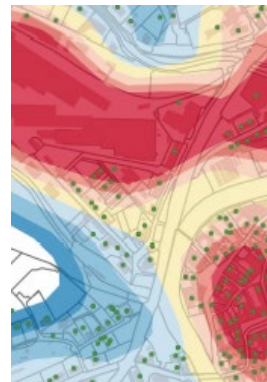
## User input

Input variables



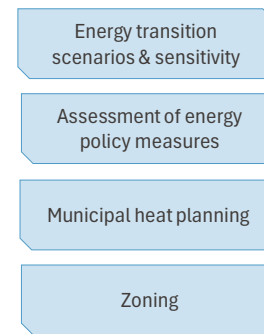
## Output

Energy demand by energy carrier, CO<sub>2</sub> emissions, etc.



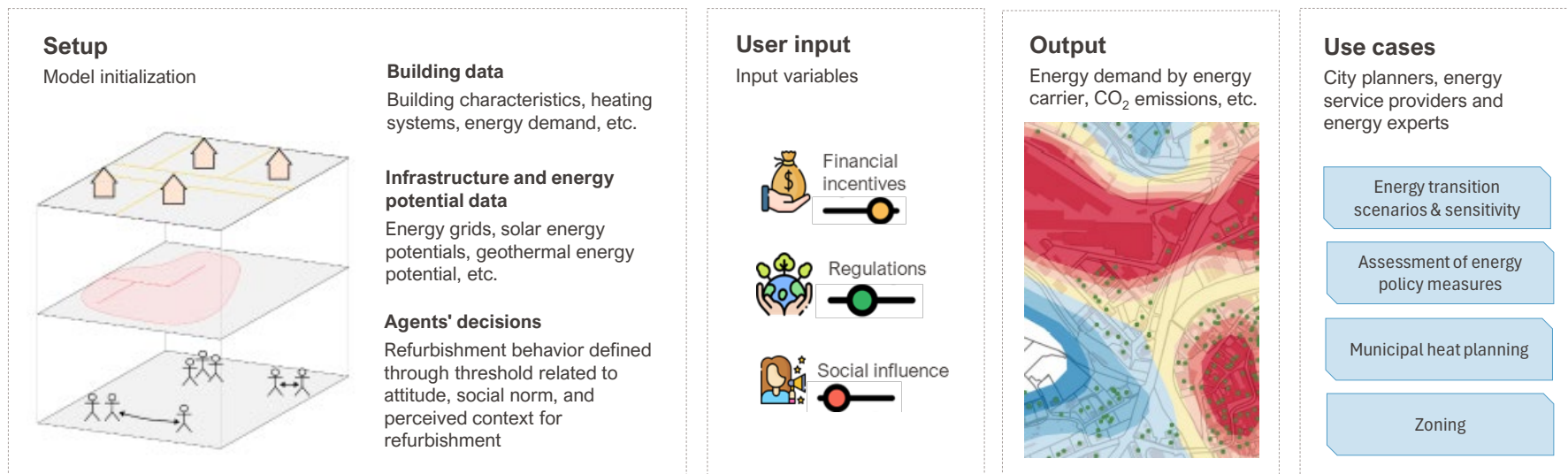
## Use cases

City planners, energy service providers and energy experts



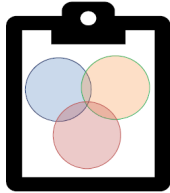
**Building renovation and heating system replacement:** additionally influenced by agents' behavior, i.e., attitude, social norm and perceived context.

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



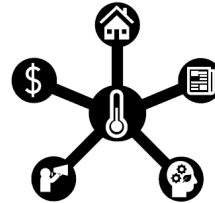
# Agents' decisions for refurbishment and heating system replacements

Online survey on energy renovation decisions



Final sample of 1,787 homeowners from across Styria

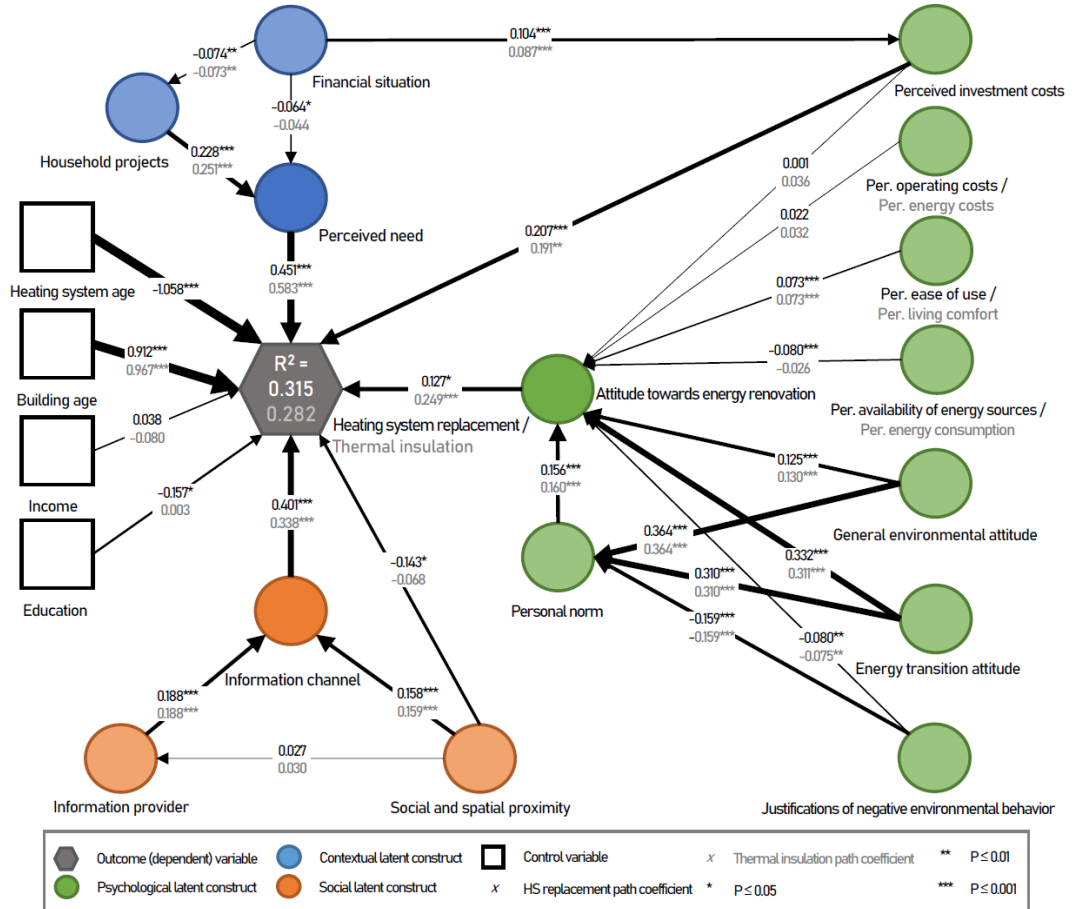
PLS-SEM to understand household decision-making



ABM empirically calibrated to support the heat transition

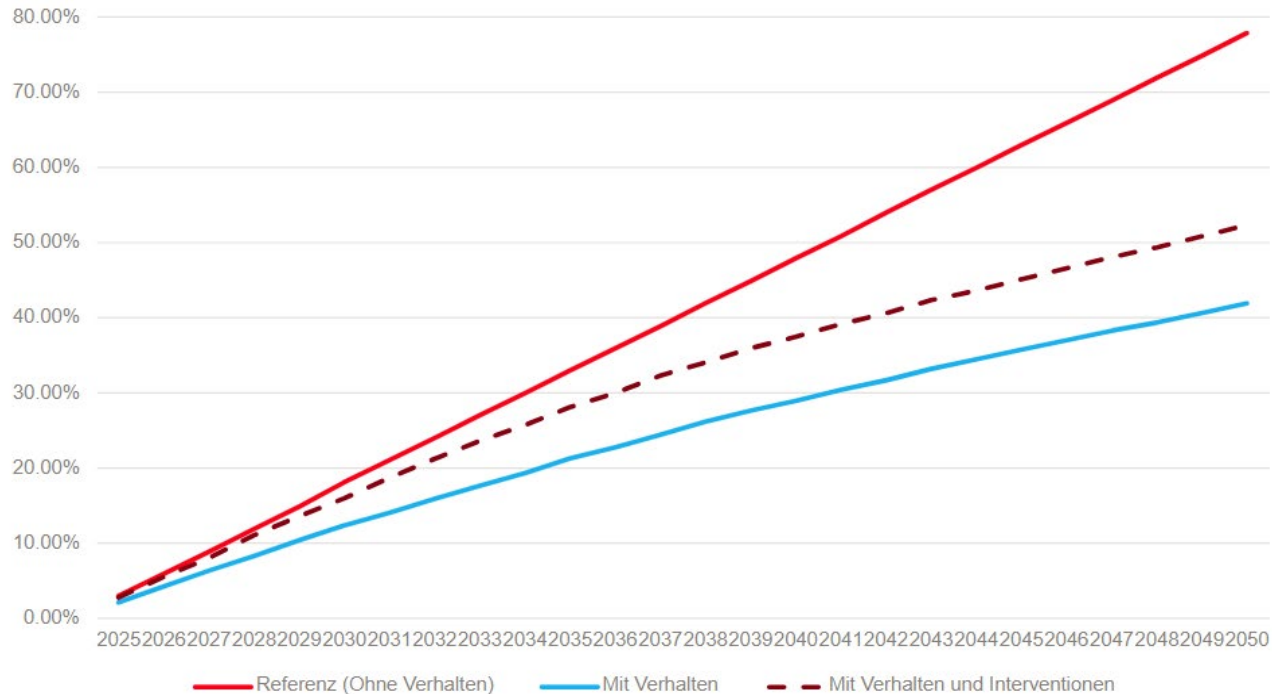
# Context, attitude and information exchange matters

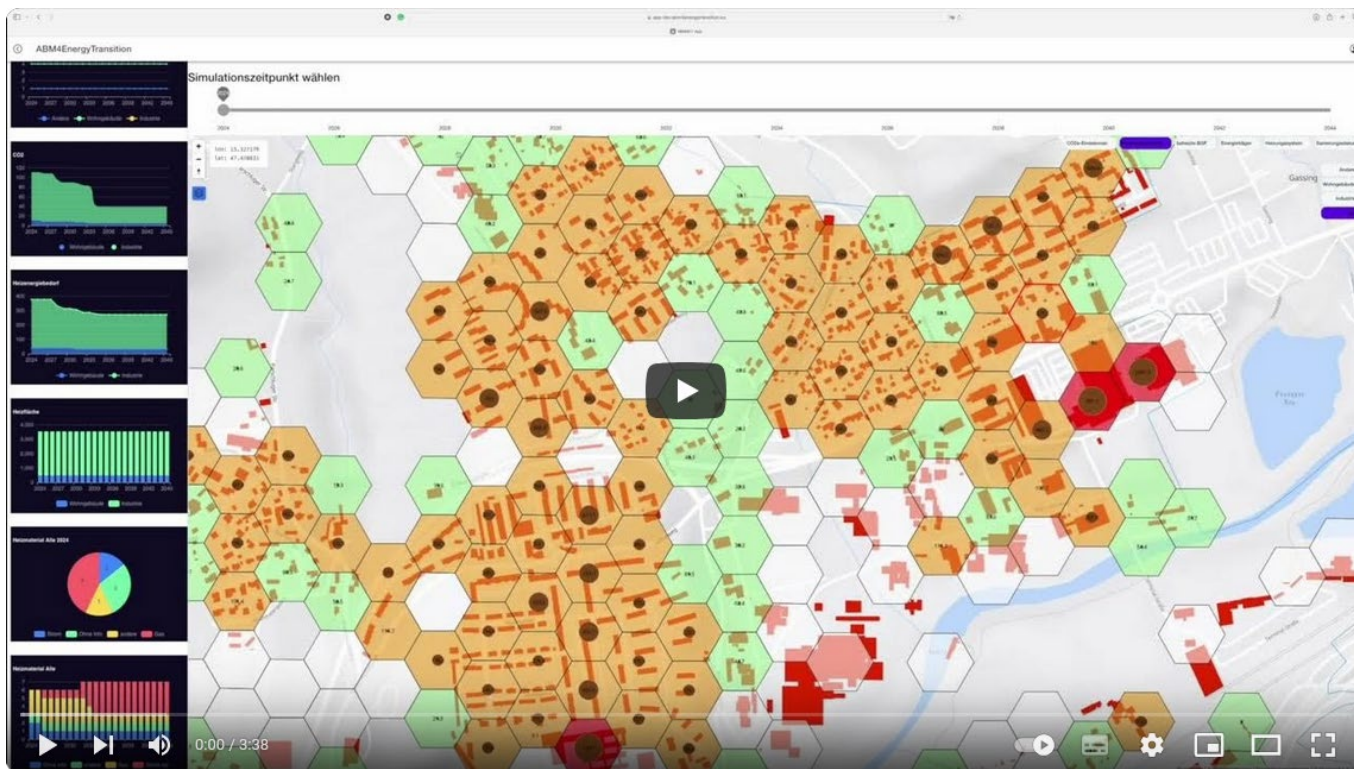
Sample of 1,787 homeowners in Styria, Austria (June - July 2023)



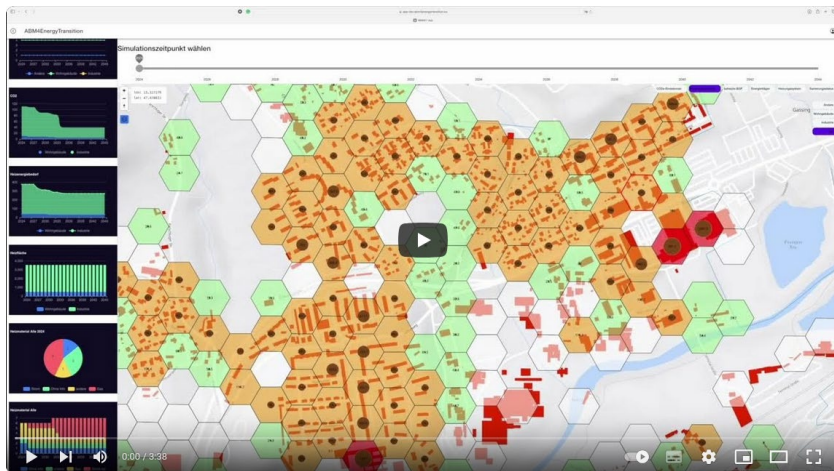
# Renovation rate: Technical vs. behavioral model

Output: Renovierungsrate (Referenzwert 3% p.a.)





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



## Application

<https://app.abm4energytransition.eu/login>

## Email

guest@abm4energytransition.eu

## Password

Willkommen2024!

# Integrated MFA in Industrial Ecology



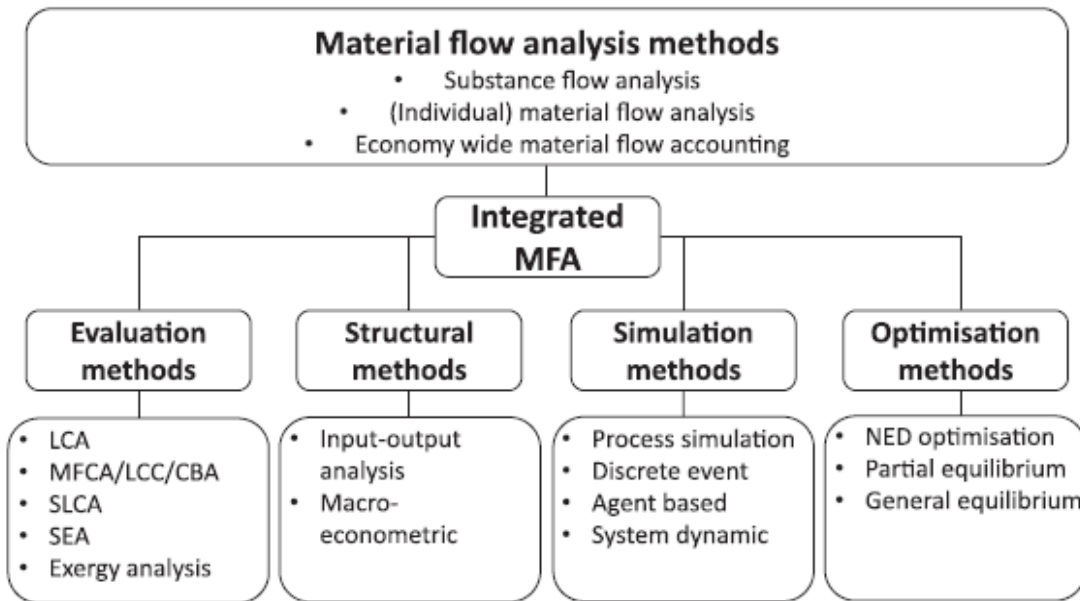
# Purpose of MFA in Industrial Ecology

- **Descriptive assessments**  
Description of past or current flows and stocks of materials in a spatial and temporal defined system.
- **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).

## Integration of economic, environmental, and social layers

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



**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

# 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)

# Purpose of integrated MFA

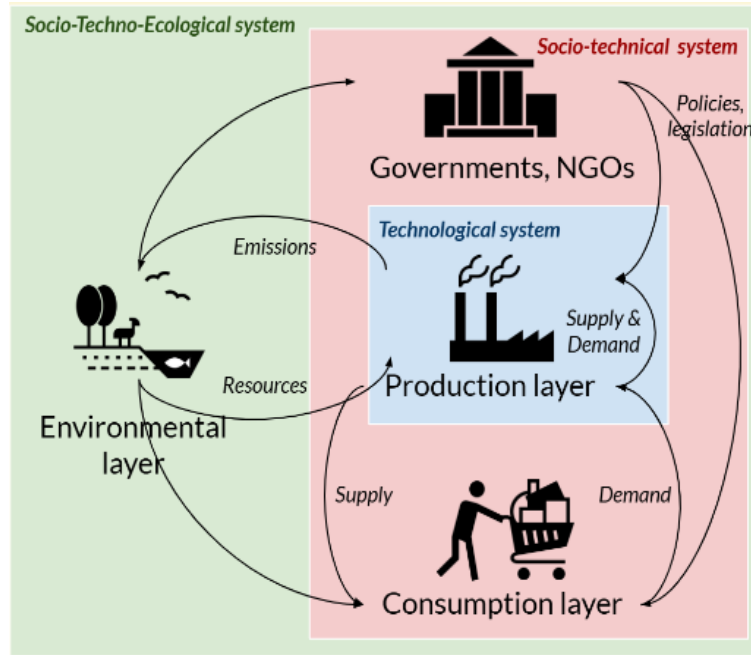
Simulation	Discrete event	Discrete simulation of material flows in the material systems
	Agent based	Simulation of material flows driven by the interaction of supply chain actors based on clearly defined rules
	System dynamics	Simulation of material flows driven by a global system behavior-based on differential 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

# Potentials of ABM in Industrial Ecology



# Why do we need ABM in Industrial Ecology?

# ABM allows to study complex systems and is taking momentum



Production and consumption systems are **complex socio-techno-ecological systems.**

# Why do we need ABM in Industrial Ecology?

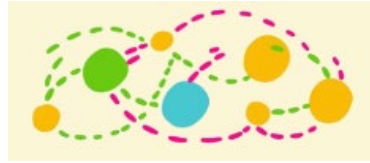
*Industrial ecology examines the behavior of complex socio-technical systems embedded within environmental and institutional contexts.*

**Recognizing system complexity is critical, as sustainability outcomes emerge from the interactions between technologies, human behavior, resource flows, and regulatory frameworks.**

# Why do we need ABM in Industrial Ecology?

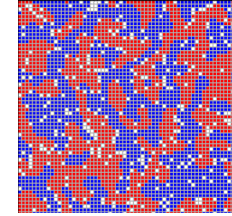
## Heterogeneous network

Multiple actors with different goals and perspectives etc.



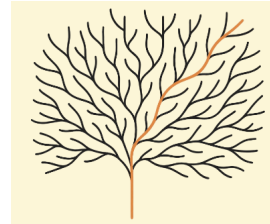
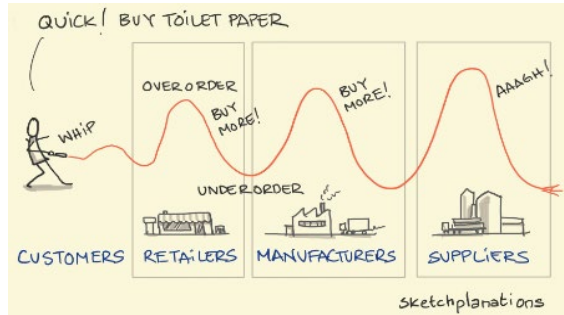
## Emergence

Global environmental impacts emerging from many decentralized actions etc.



## Non-linear dynamics

Efficiency improvements may lead to rebound effects, policy incentives may produce unintended side effects etc.

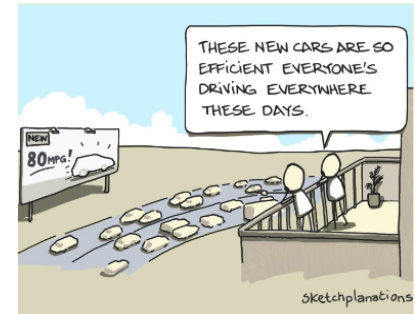


## Path dependence

Lock-in to carbon-intensive infrastructures, historical policy shaping future transitions etc.

## Adaptation

Consumers adapting to new product designs or pricing etc.



# Example: Model 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 e.g., battery costs or social dynamics.
- **Linked outcome:** ABM provides dynamic EV adoption rates, enabling MFA to estimate changing battery material demand.



# Example: Model urban recycling behaviors and resource use

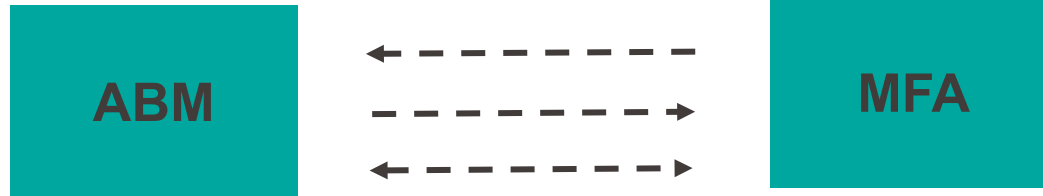
- **MFA:** Tracks materials like plastics estimating available stocks for recycling.
- **ABM:** Models consumers recycling behavior based on elicited rules.
- **Linked outcome:** ABM shows recycling adoption under different incentives, informing MFA on recycled material stock over time.



# Benefits of linking ABM and MFA

## Policy modeling

ABM-MFA integration provides insights into how policy scenarios might recycling rates and material demands over time.



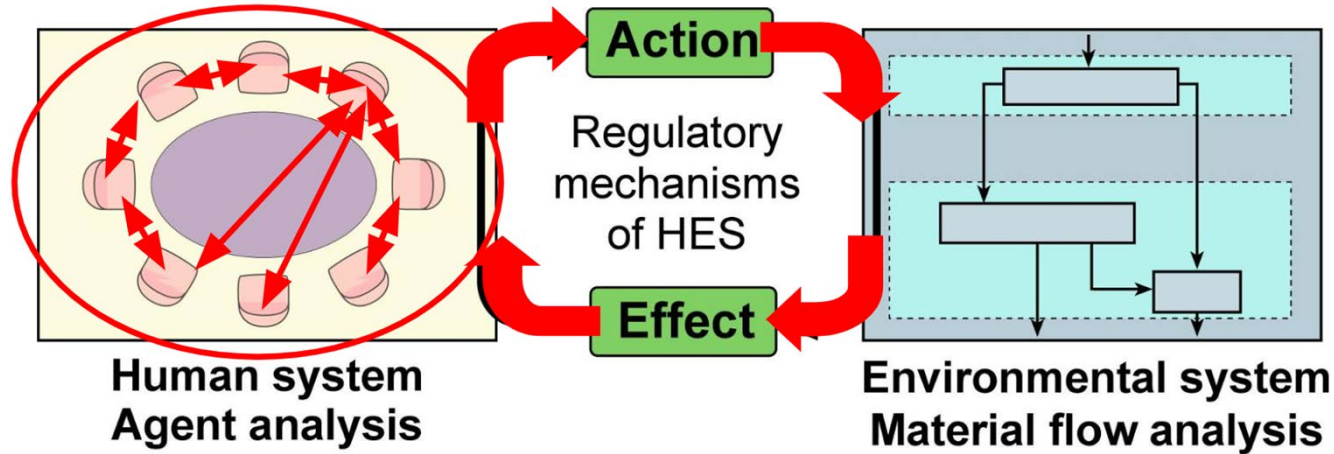
## Behavior-driven updates

ABM informs MFA with realistic adoption rates and behavior patterns.

## Adaptive feedback

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

# Benefits of linking ABM and MFA



Binder, 2005

- Understand the key characteristics of Agent-Based Models (ABM) and their application fields
- Recognize the purpose of ABMs in Industrial Ecology and its added value

## In-depth evaluation survey SA25/26

- ✦ Opportunity for students to provide comments
- ✦ Log into Moodle and stay on the Moodle home page (dashboard, not the course page).
- ✦ Click on the arrow to the top right of the screen → “In-depth evaluation” tile
- ✦ Select ENV-501 and complete the feedback.

**Log into Moodle**

<https://moodle.epfl.ch/login/index.php>

**Also via the  
EPFL Campus  
App**

- **Weinberger, G., Ladino Cano, S., Hecher, M., Mauthner, F., Scholz, J., 2025.** Simulating heat transition scenarios using agent-based modeling. *gis.Science*
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