Introduction to System Dynamics Modelling – day 2

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COMPLEX SYSTEMS AND NETWORK SCIENCE FOR PREVENTION AND CONTROL OF NONCOMMUNICABLE DISEASES

A WHO COLLABORATING CENTRE FOR RESEARCH AND TRAINING

GroundsWell

Transforming our cities from the ground up

Outline of the day

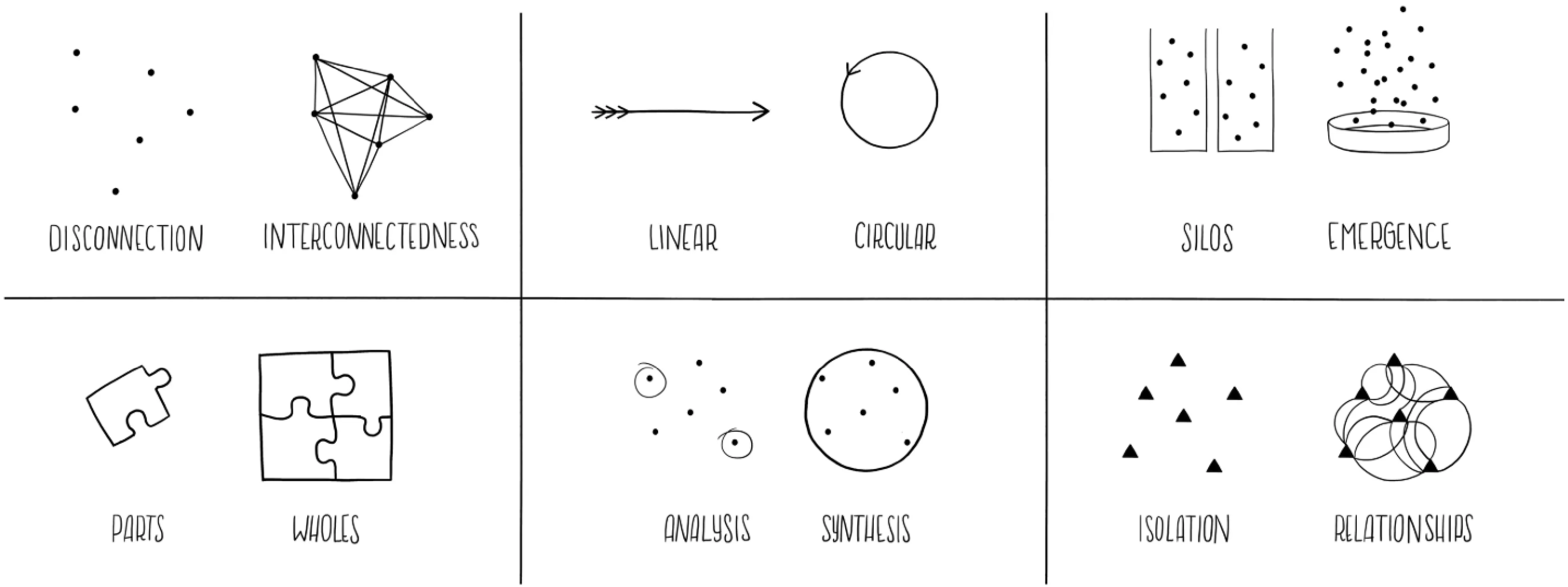
- Recap of session 1 (10 min) - Mehdi
- Stock and flow diagramming (20 min) - Mehdi
- Behaviour patterns (15 min) - Mehdi
- Q&A (10 min)
- Comfort break (5 min)
- Demonstration of building a public health model (20 min) - Leandro
  - Using data to inform your model (10 min) - Leandro
  - Analysing and visualising outputs (10 min) - Leandro
- Q&A (15 min)
- Closing (5 min) - Leandro

Foundations of systems thinking / system dynamics

What is systems thinking?

- Way of thinking and doing based on systems concepts and methods
- **Core principle:** breaking the system down to its parts does not allow us to fully understand the whole system
- Active focus on structures, interconnections, processes, mechanisms, and context
- It is about seeing the 'bigger picture'

Mindset of a systems thinker



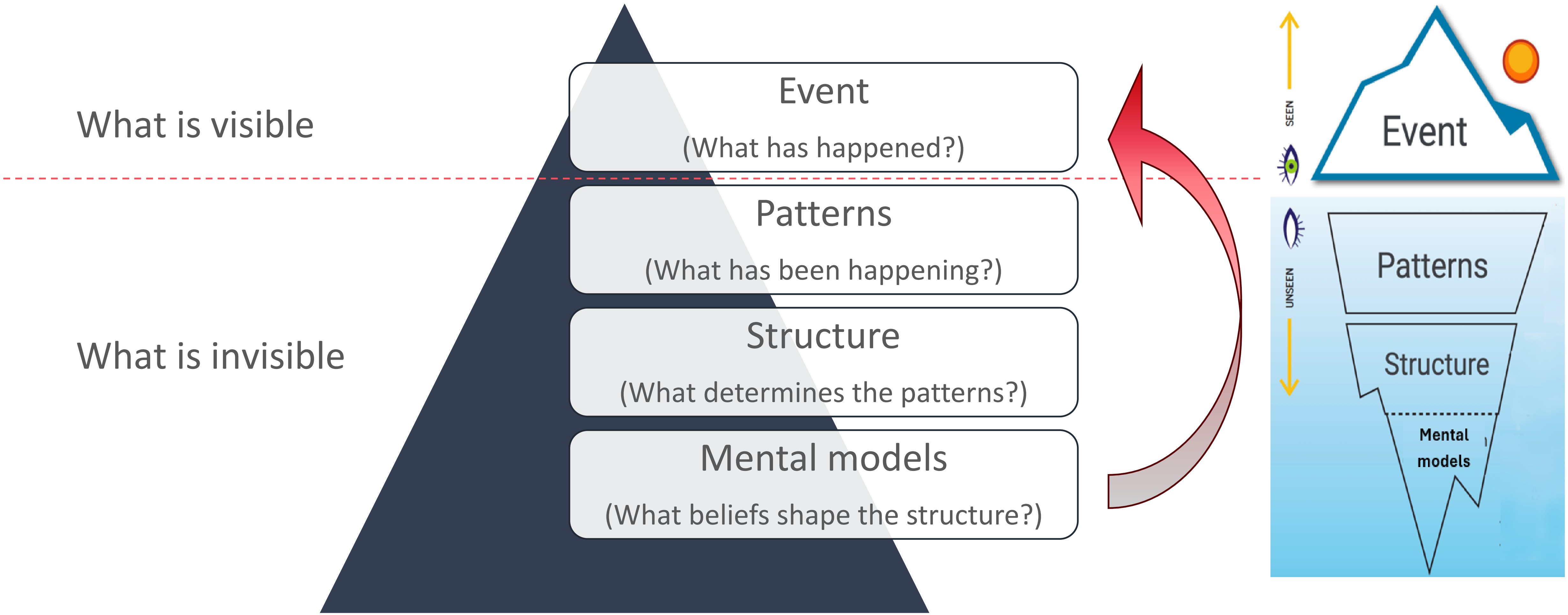
https://medium.com/disruptive-design/tools-for-systems-thinkers-the-6-fundamental-concepts-of-systems-thinking-379cdac3dc6a

Why systems-based public health?

Proposition: Modern societies are complex systems

Implication 1: Many public health challenges emerge from how modern societies (complex systems) are organized

Implication 2: Interventions are actions within a complex system



"Instead of asking whether an intervention works to fix a problem, we should aim to identify if and how it contributes to reshaping a system in favourable ways."

Rutter H et al. The need for a complex systems model of evidence for public health. Lancet. 2017;390(10112):2602-4.
https://durmonski.com/self-improvement/iceberg-model-systems-thinking

DYNAMIC THINKING

Closed (Dynamic) vs Open (Linear) Thinking

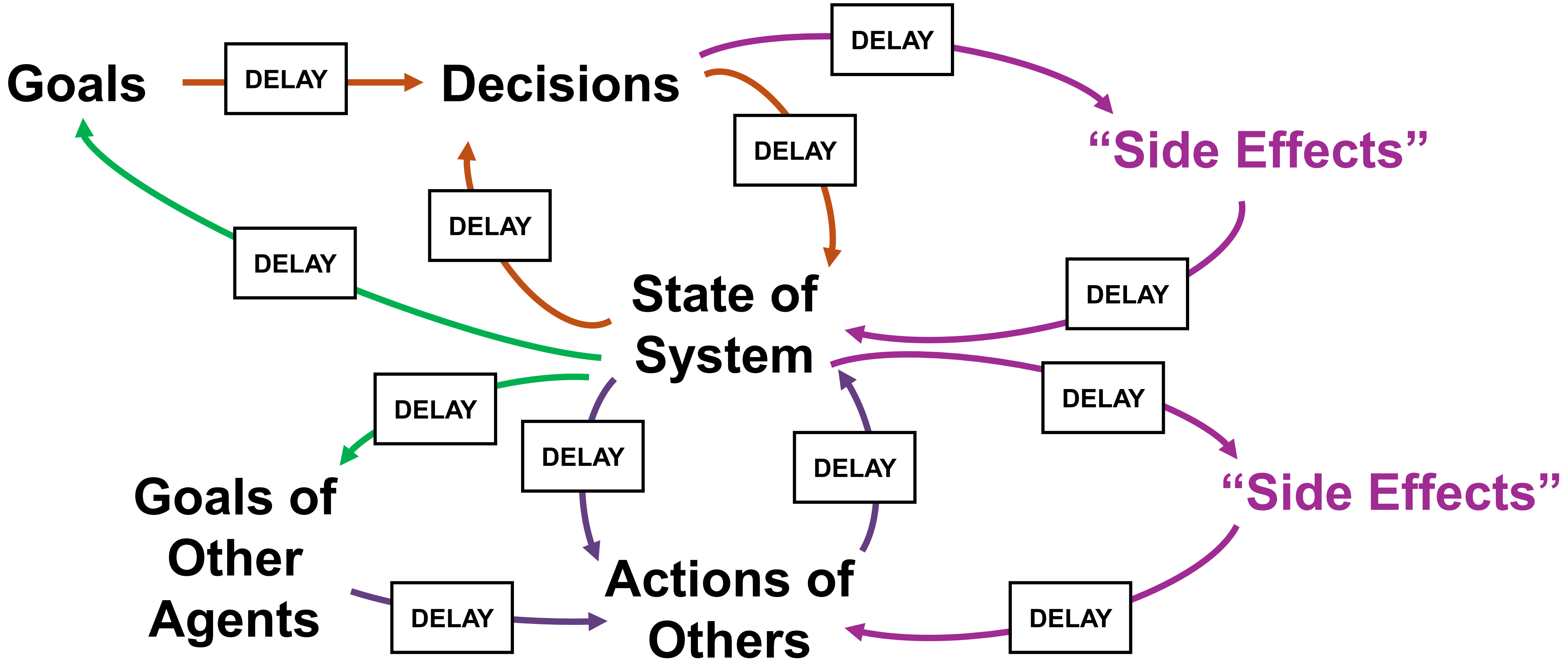
Event-oriented view of the world

Closed loop VS. Open loop

Goals → Decisions → State of System

Adapted from Sterman (2000)

System (Dynamic) Thinking



Adapted from Sterman (2000)

Closed-loop (Dynamic) Thinking

Closed (Dynamic) vs Open (Linear) Thinking

Concept	Linear Thinking	System Dynamics Thinking
Focus	Single events	Patterns and structures
Causality	One-way cause → effect (A → B → C → D)	Circular feedback loops (A ↔ B ↔ C ↔ D ↺)
Focus	Isolated events	Interconnected structure
Time	Static snapshot (short time)	Evolving over time (Long-term)
View of Change	Quick fixes	Sustainable solutions

WHAT IS A SYSTEM?

For this session and from System Dynamics view, we define a 'system' as:

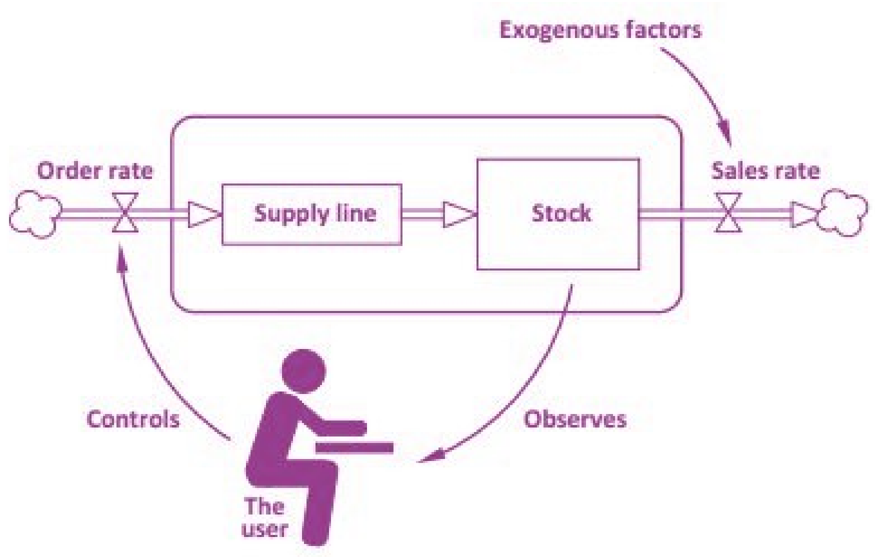
A network of interdependent components connected by feedback relationships, whose structure generates its dynamic behaviour over time.

Jay W. Forrester, Industrial Dynamics (1961)

WHEN DO WE WANT A SYSTEM DYNAMICS SIMULATION MODEL?

There is a challenge, and we want to:

- increase our understanding of a problem
- Improve existing systems
- Improve behaviours
- Reduce complexity
- Avoid black-box decision making



SD FUNDAMENTALS

SD is not a tool but rather an approach ….

Social, health and economic systems are:

- Dynamic
- Tightly coupled
- Nonlinear and Governed by feedback
- Delays in cause and effect

- **No system exists in isolation**
- **Mental models are key drivers**

QUALITATIVE VS. QUANTITATIVE SYSTEM DYNAMICS

Qualitative SD

- Causal Loop, feedback or Influence Diagrams
- Feedback Loops
- Structure Generating Behaviour

Quantitative SD

- Stock and Flow Modelling
- Feedback and Delay
- Underpinning Mathematics
- Simulation

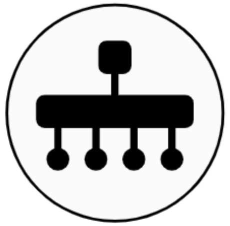
Two equivalent models that describe a system

A STRUCTURED APPROACH TO SYSTEM DYNAMICS*

Qualitative System Dynamics

Problem Definition

Formulate and scope the problem for dynamic modelling

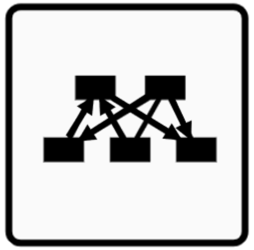


Variables

Recognise and identify the key variables and underlying factors

Behaviour over time

Recognise and estimate the behaviour of key variables over time



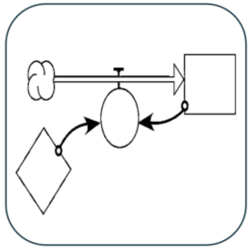
Feedback diagram

Identify cause and effect, draw feedback diagrams
(Causal loop diagram)

* Zimmermann, N. (2021). Introduction to Modelling Process Seminar Series, System Dynamics Society, UCL

A STRUCTURED APPROACH TO SYSTEM DYNAMICS

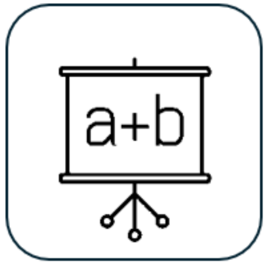
Quantitative System Dynamics*



Stock and Flow Diagramming

Identification of stock and flows and their interrelationships

→



Model formulation

Integrations of stocks and policies of flows

→

Simulation

Generate model behaviour over time

→

Analysis and implementation

Compare real and simulated behaviour, test structure, identify and test policy alternatives, and implement changes in the real system

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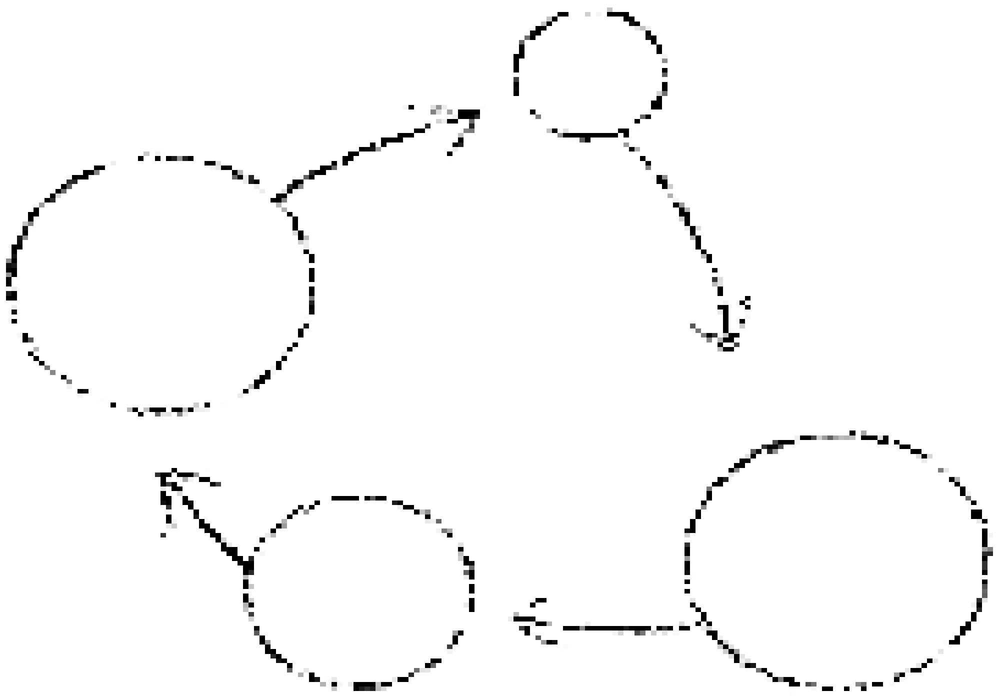
Foundations of systems thinking

Introduction to System Dynamics

Qualitative System Dynamics (CLD)

Quantitative System Dynamics



With acknowledgements to Dr Natalie Clewley and the Cranfield teaching team
Course Director of Systems Thinking Practice at Cranfield University

Causal loop diagrams

CAUSAL LOOP DIAGRAMS

- ❑ **Variables:**

These are the key elements or factors within a system that change over time.

- ❑ **Arrows (Causal Links):**

Arrows connect the variables and show a causal relationship, indicating that a change in one variable affects another.

- ❑ **Feedback Loops:**

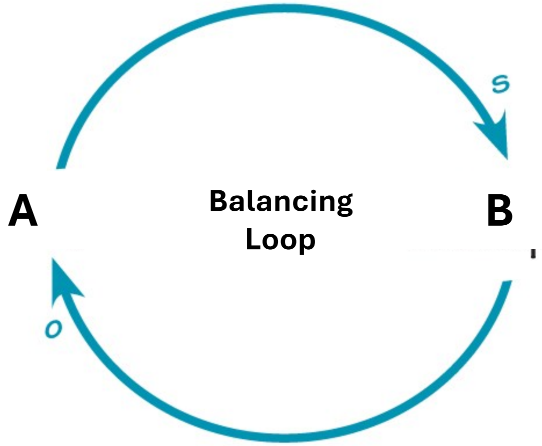
A feedback loop is created when causal links **form** a closed circle or loop.

- ❑ **Time Delays**

These are often represented by a symbol on a link and indicate that a causal relationship takes time to manifest its effect.

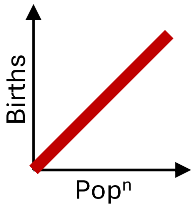
CLD Variables are:

- Clear
- Objective
- Unambiguous



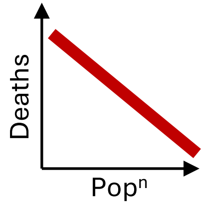
CLD - ARROWS

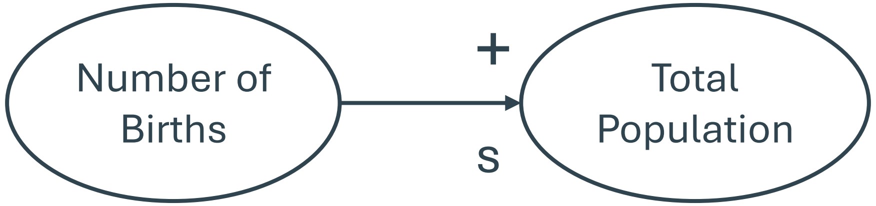
The connecting arrows between variables or nodes within the system indicate a **positive or negative <u>correlation</u> between variables**, signifying how a change in one variable will affect another.

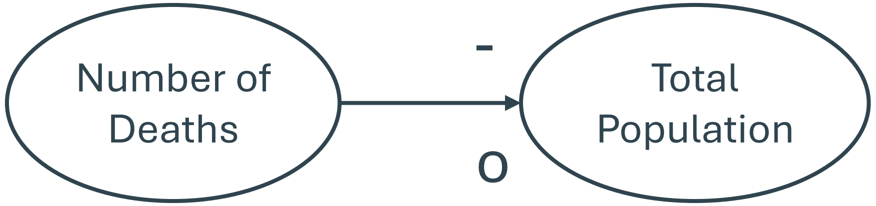


A **positive correlation/coupling** moves the variable values in the same direction. This can be represented by '+' or 's' for the same direction.

A **negative correlation/coupling** moves the variable values in opposite directions. This can be represented by '-' or 'o' for opposite direction



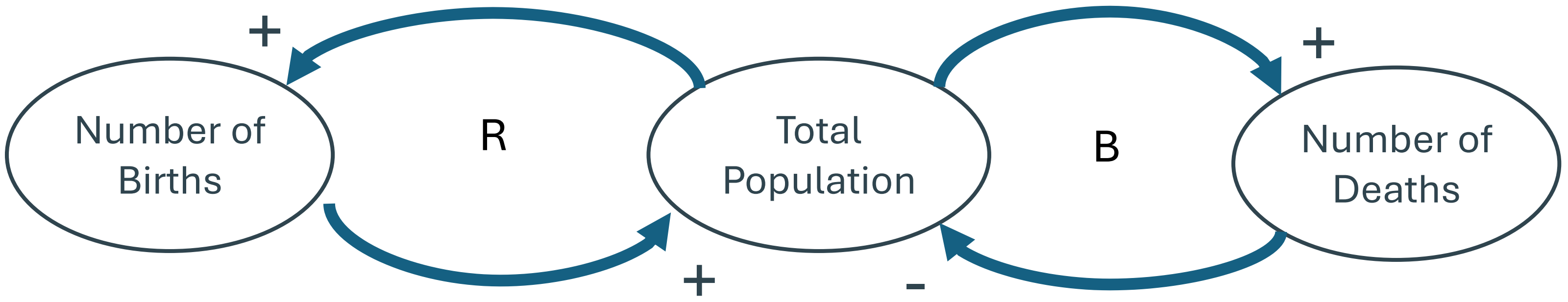




For example, an *increase* ↑ in births causes an *increase* ↑ in the population (+ positive coupling) whereas an *increase* ↑ in deaths causes a *decrease* ↓ in the population (- negative coupling).

CLD - FEEDBACK LOOPS

Causal loops enable us to think about feedback, delay and non-linearity in the behaviour of a system.



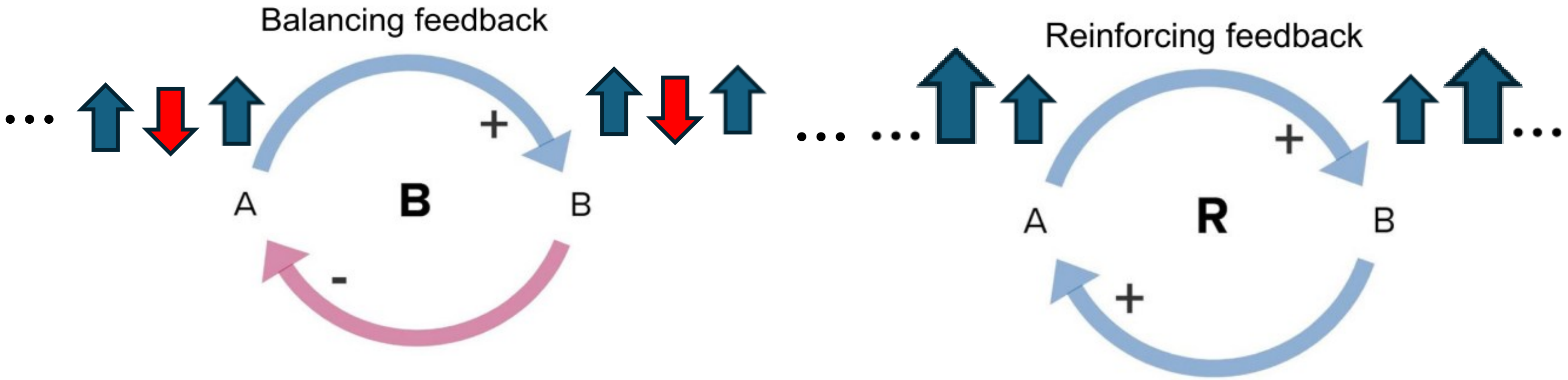
CLD - FEEDBACK LOOPS

Feedback loops can be BALANCING or REINFORCING in nature.

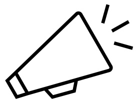
- **Balancing (B) behaviour**, where the initial change is counteracted, also referred to as negative feedback or goal seeking.

Reinforcing (R) behaviour, where an initial increase in the first component is further increased.

Reinforcing (R) behaviour, where an initial decrease in the first component is further decreased, also referred to as declining, decaying



Balancing loops are created when there is an odd number of negative couplings! Otherwise Reinforcing loops are created !



EXAMPLE (2)*

The Real Estate Game
Available houses

1. Problem Definition:

To estimate the available houses within a region in the next 100 months.

NEXT: Variables and Feedback diagram (CLD)

* https://www.vensim.com/documentation/20760.html

EXAMPLE (2)*

The Real Estate Game

1. Problem Definition:

To simulate ***the available houses*** within a region in the next 100 months.

2. Variables Identification

Key Variables

- ✓ Available Houses
- ✓ Gap in Houses
- ✓ Replacement Houses
- ✓ Demolishing
- ✓ Average House Life
- ✓ Planning and Approvals
- ✓ Planned Houses
- ✓ Construction
- ✓ Houses in Construction
- ✓ Completing

Delays

- ✓ Time to Plan to Build
- ✓ Time to Build Houses
- ✓ Time to Respond to Gap

* https://www.vensim.com/documentation/20760.html

Causal Loop Diagram

EXAMPLE (2)*

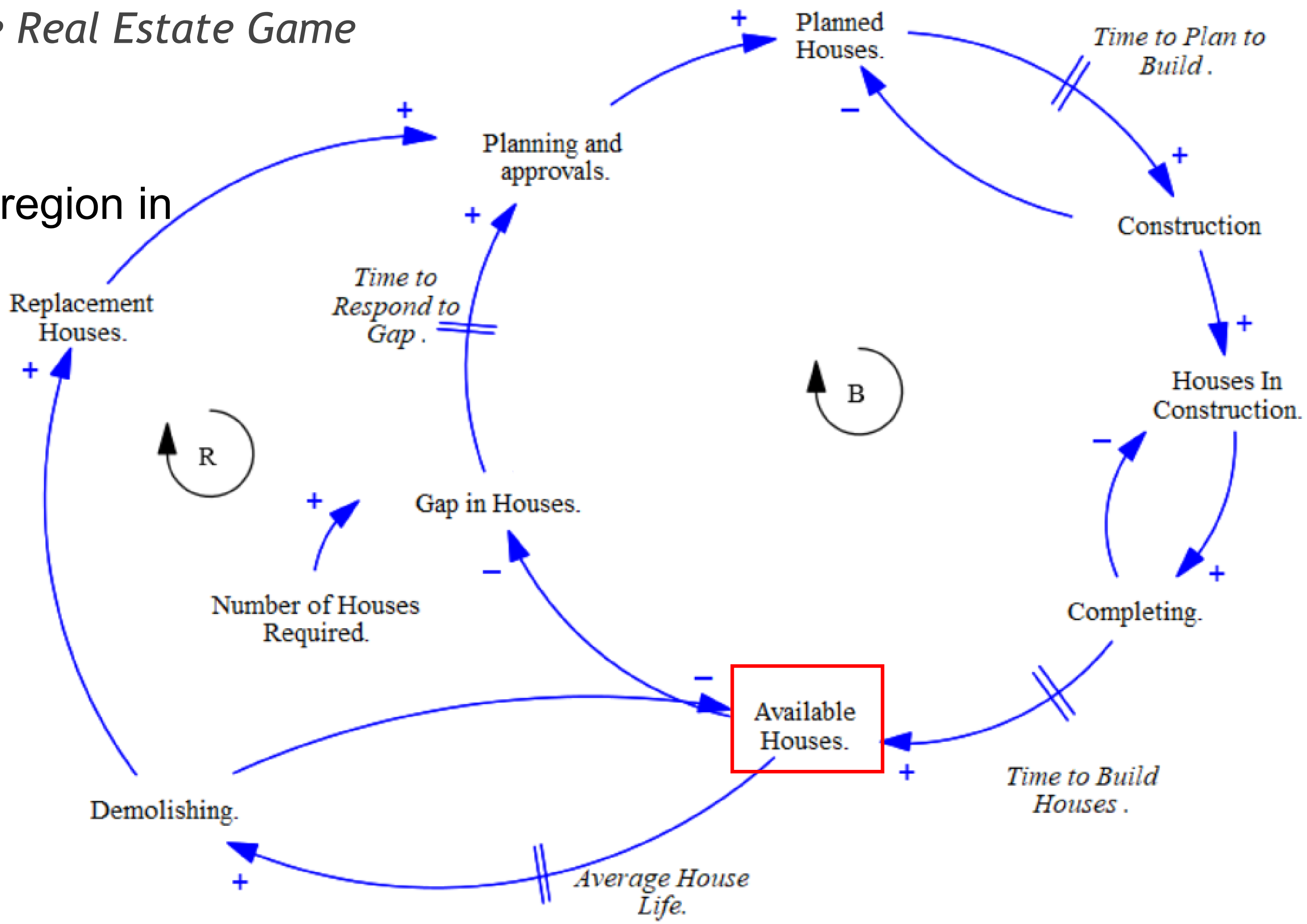
The Real Estate Game

1. Problem Definition:

To simulate ***the available houses*** within a region in the next 100 months.

2. Variables Identification

3. Feedback diagram



Causal Loop Diagram

* https://www.vensim.com/documentation/20760.html

SD MODELS

A model structure should (Forrester, 1961):

- Be able to describe any statement of cause-and-effect relationships across the system.
- Be simple (practical) in mathematical nature.
- Be able to incorporate feedback and delays within a system
- Be extendable to large numbers of variables without exceeding practical computing limits.
- Be able to handle ‘continuous’ interactions.

The First Law of Modelling states that if you don’t understand a system’s key feedback loops, then you don’t understand the system.

Foundations of systems thinking

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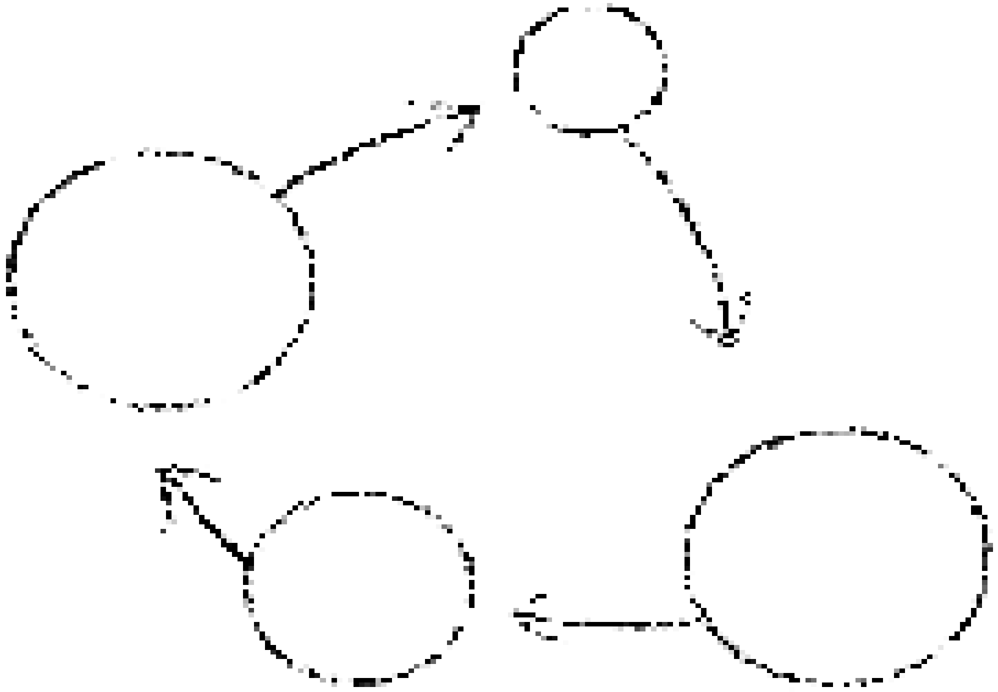

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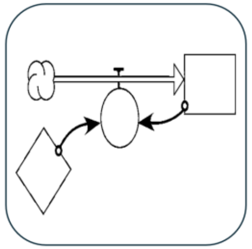
A STRUCTURED APPROACH TO SYSTEM DYNAMICS

Quantitative System Dynamics



Stock and Flow Diagramming

Identification of stock and flows and their interrelationships

Model formulation

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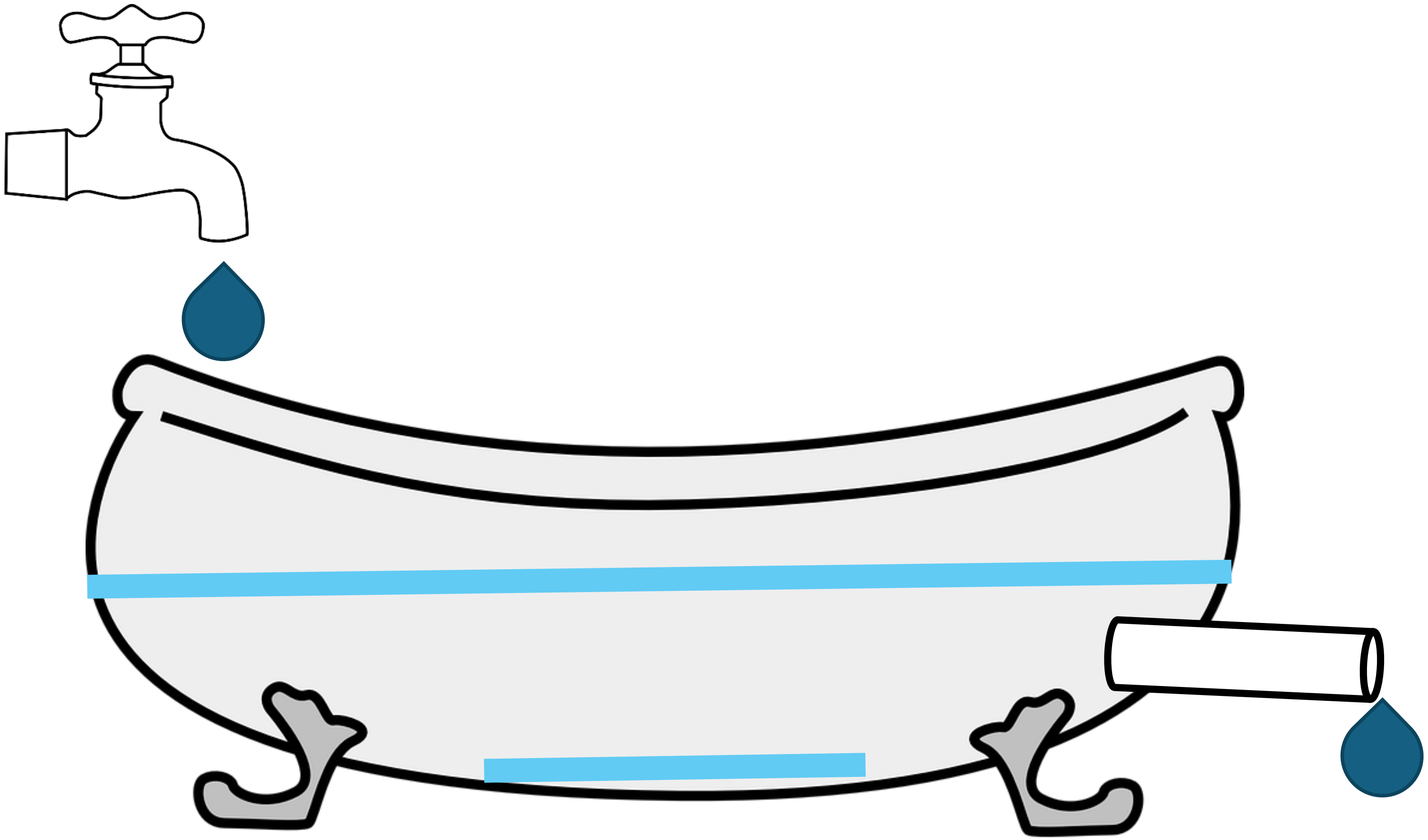
THE BATHTUB METAPHOR



ACCUMULATIONS (STOCKS) ARE ALL AROUND US…

Number of students in a class

Desks

Level of happiness

OR

Water in the lake

Cows in a grass field

Area covered by grass

A stock is a quantity that accumulates or depletes over time. It represents the “state” of a system at any given moment.

STOCKS AND FLOWS COMPONENTS

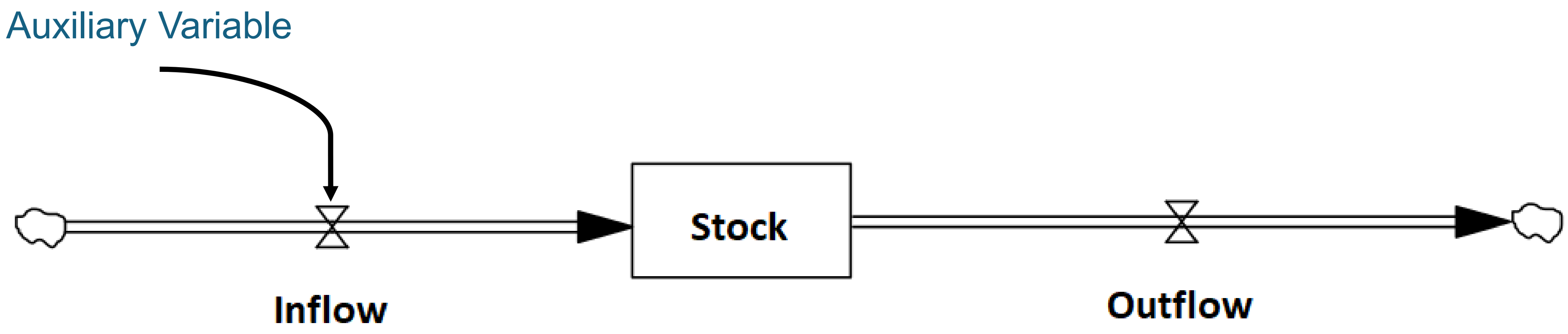
The main components of a stock-and-flow diagram

- **Stocks** (also called "**Levels**" or "**Accumulations**" or "**state variable**")
- **Flows** (also called "**Rates**") = *(Stock amount/time intervals)*
- **Auxiliary** variables (also called "**Converters**" or "**Dynamic variables**" or "**Parameters**")
- **Links**
- **Sinks, also called "source"**, represent flows from outside the system or into it.

Why SFD?

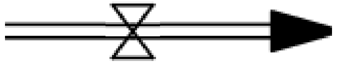
- Causal Loop Diagrams are good for capturing interdependencies and feedback processes within a system.
  - CLDs do not, however, take into account stocks and flows in the system (current status).

STOCKS AND FLOWS COMPONENTS



- **Stock / Level**

- **Auxiliary Variables and links**

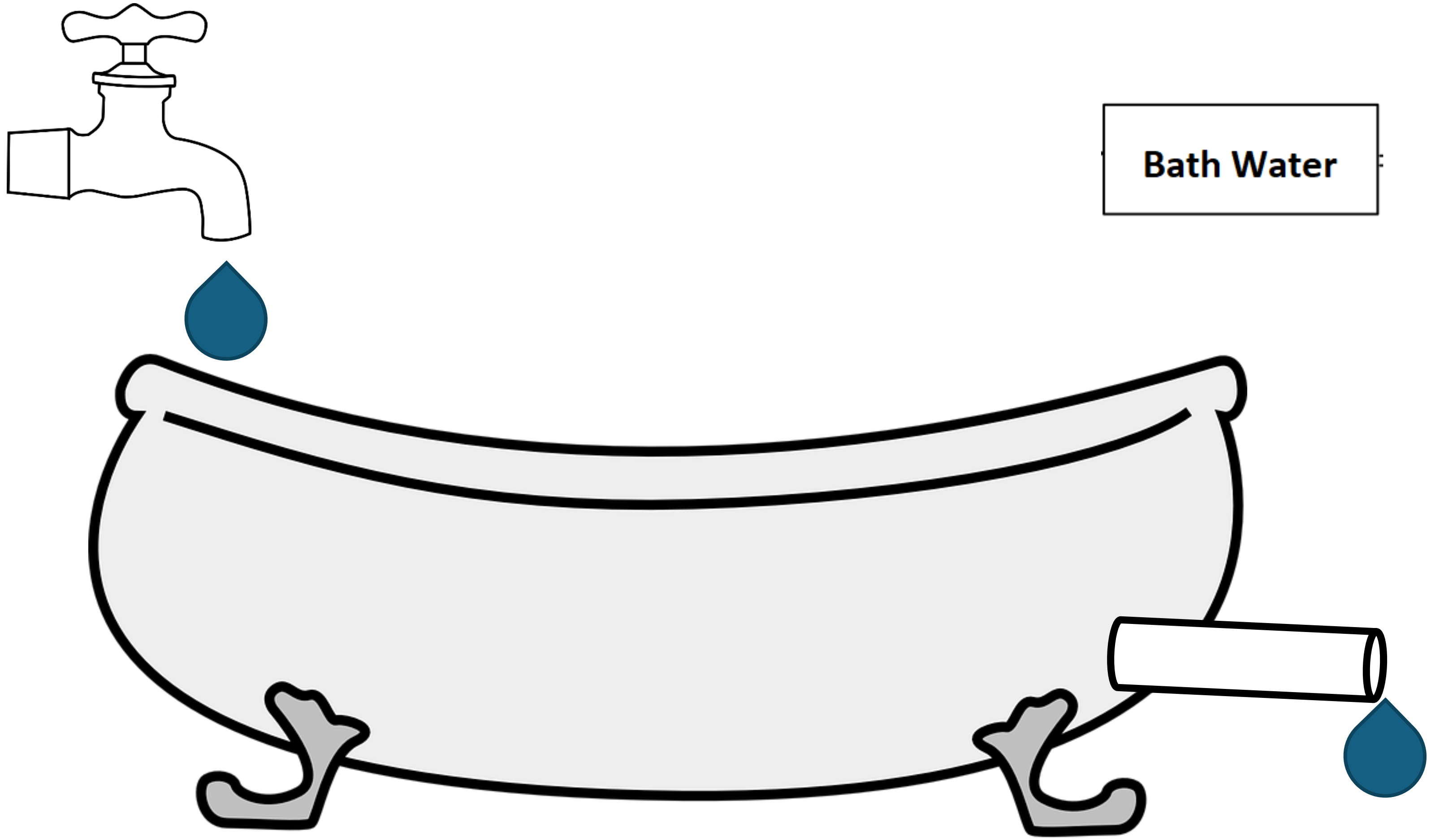


- **Flow**

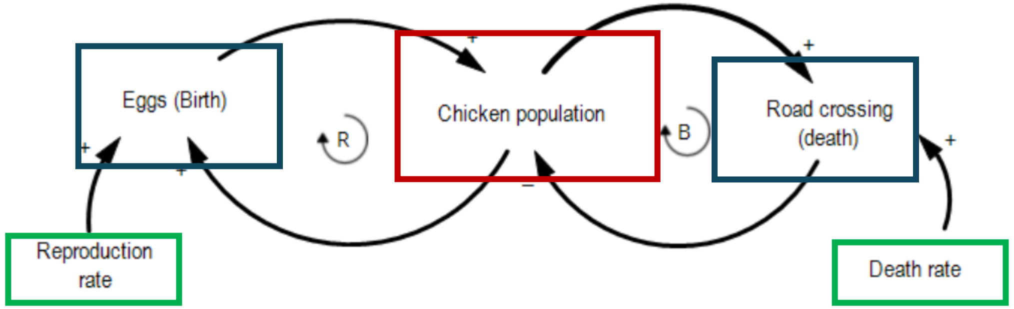
Valve (Flow Regulator)

- **Sink (Inside) or Source (Outside)**

THE BATHTUB METAPHOR



CLD to SFD (Chicken Population Example)

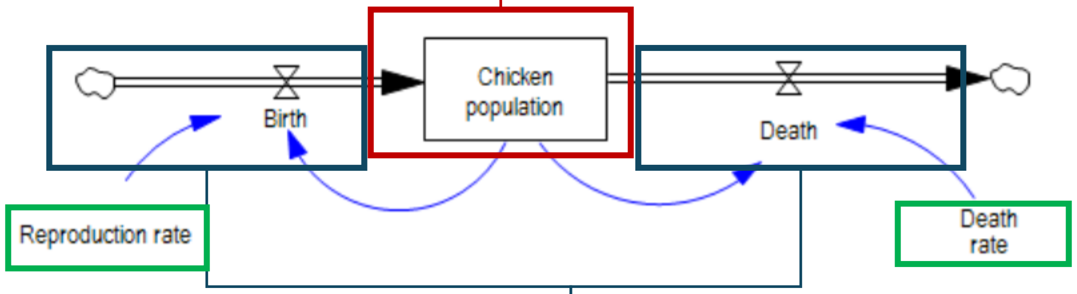


Stock

Flow

Auxiliary Variable

Stock: stuff that accumulates or depletes over time



Flows: rates of change in a stock (inflow and outflow)

Important rule

- There is an implicit **POSITIVE** causal link from an inflow to its corresponding stock!
- There is an implicit **NEGATIVE** causal link from an outflow to its corresponding stock!

These causal links are not usually drawn on an SFDs, but it is implied to exist.

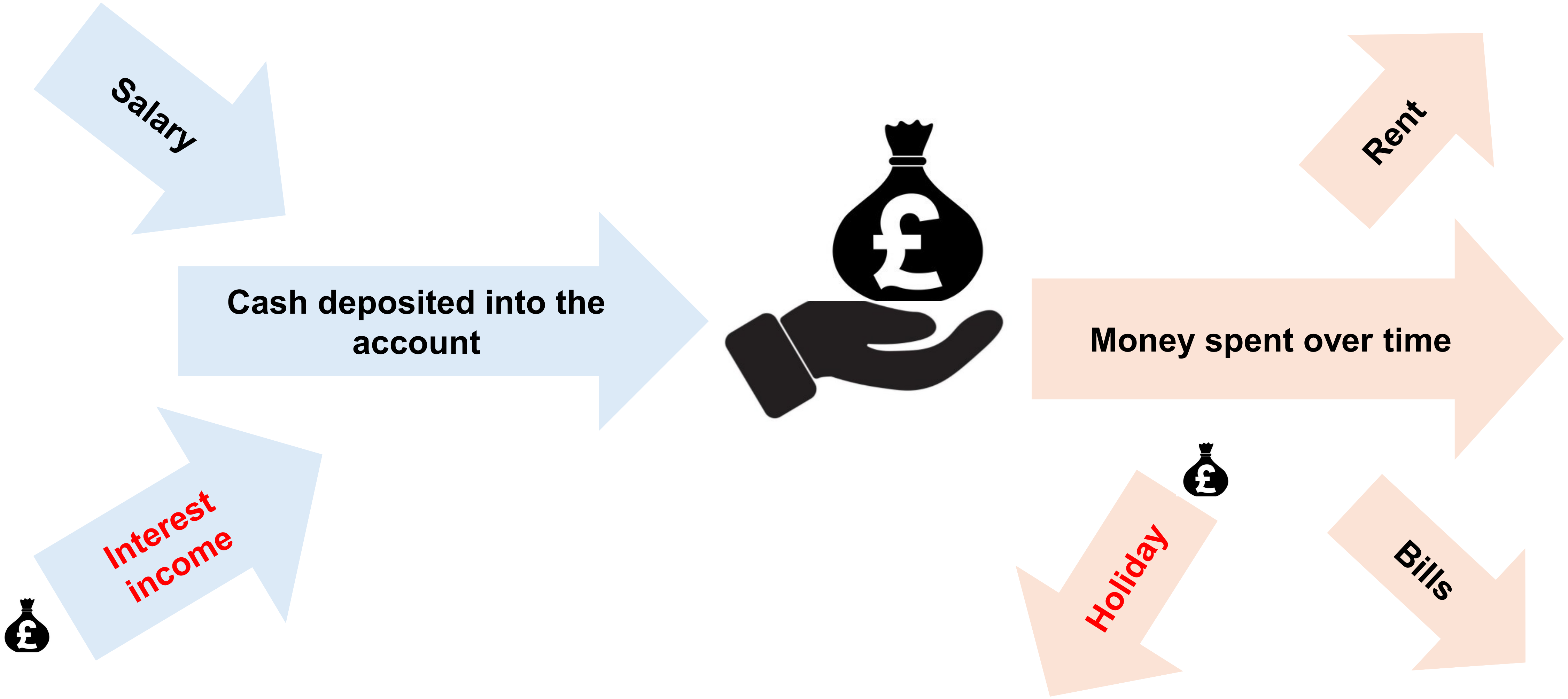
Auxiliary variables: important for calculations, but not a stock or flow

EXERCISE

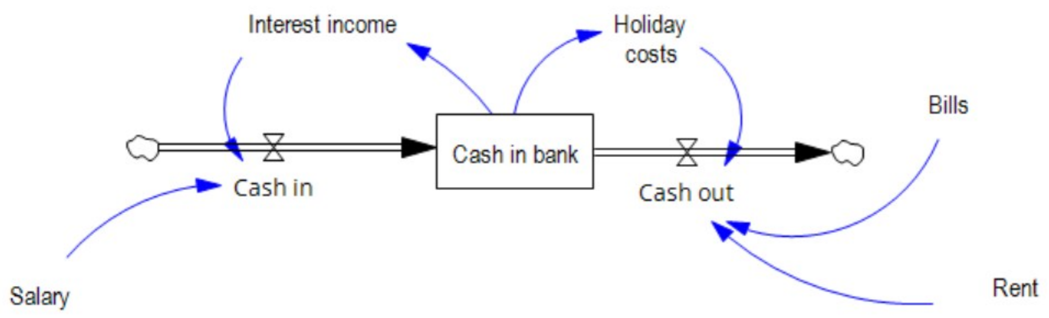
Assumptions: You have two major sources of income, including *salary* and *interest income from bank*, and three major categories of expenses, including (1) *rent,* (2) *bills* and (3) *holiday costs depending on our budget.*

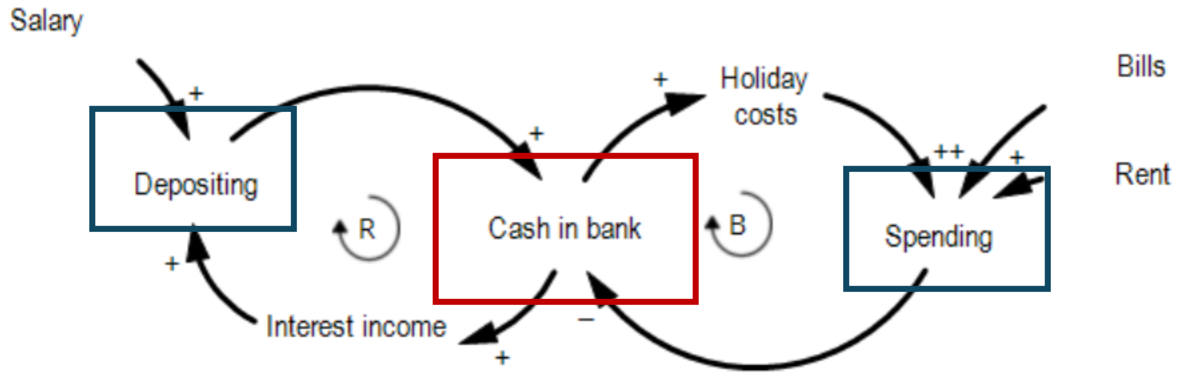
Task: Develop a Causal Loop Diagram (CLD) showing regular changes in cash in bank and then construct the corresponding Stock and Flow Diagram (SFD).

STOCKS AND FLOWS: BANK ACCOUNT EXAMPLE



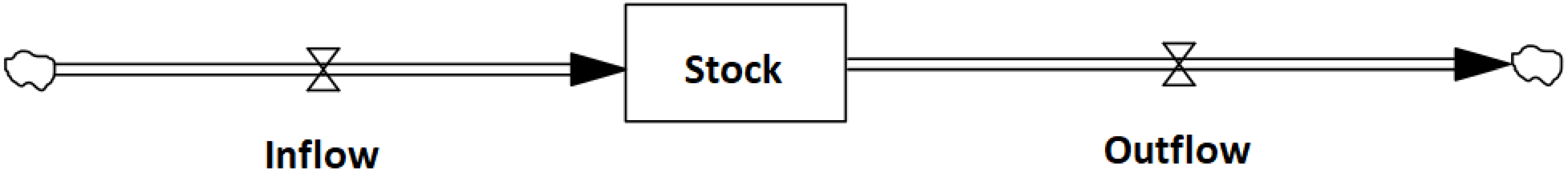
STOCKS AND FLOWS: BANK ACCOUNT EXAMPLE





STOCK AND FLOW EQUATIONS

Stocks and flows can be precisely and unambiguously represented by mathematical equations.



Stocks accumulate (or integrate) their flows.
Integral Equation:

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock\ (t_0)$$

where Inflow(s) represents the value of inflow at any time s between the initial time t_0 and the current time t.

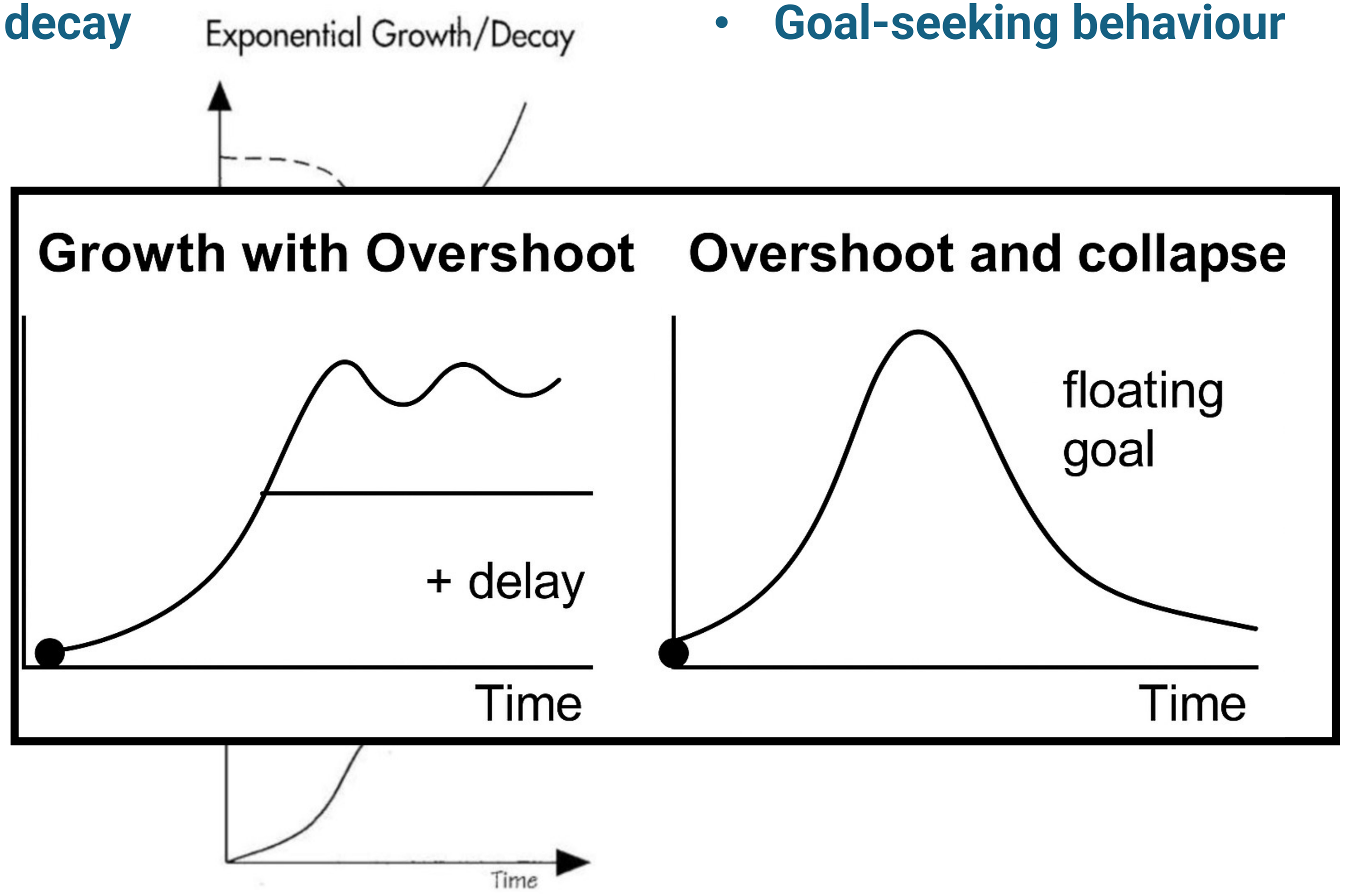
The net rate of range in any stock (its derivative), is the inflow less the outflow.
Differential Equation:

$$\frac{d(Stock)}{dt} = Net\ change\ in\ Stock = Inflow(t)\ - Outflow(t)$$

Behavior Patterns

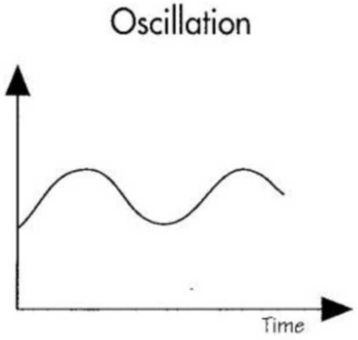
FUNDAMENTAL MODES OF DYNAMIC BEHAVIOUR

- Exponential growth or decay



- Goal-seeking behaviour

- S-shaped growth

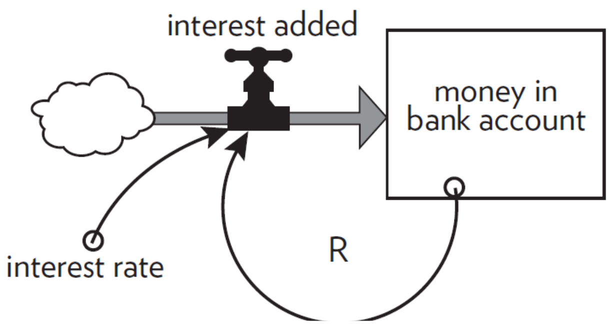


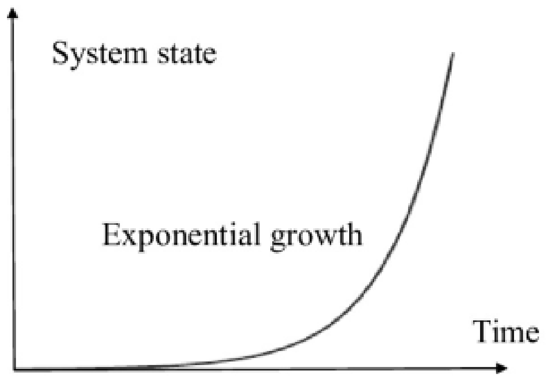
Ref: Williams, B., & Hummel brunner, R. (2010). Systems concepts in action: a practitioner's toolkit. Stanford University Press.

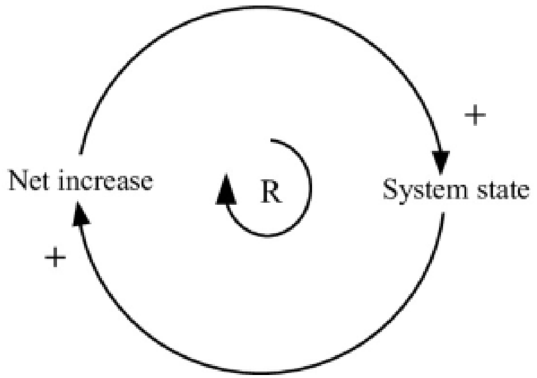
FUNDAMENTAL MODES OF DYNAMIC BEHAVIOUR

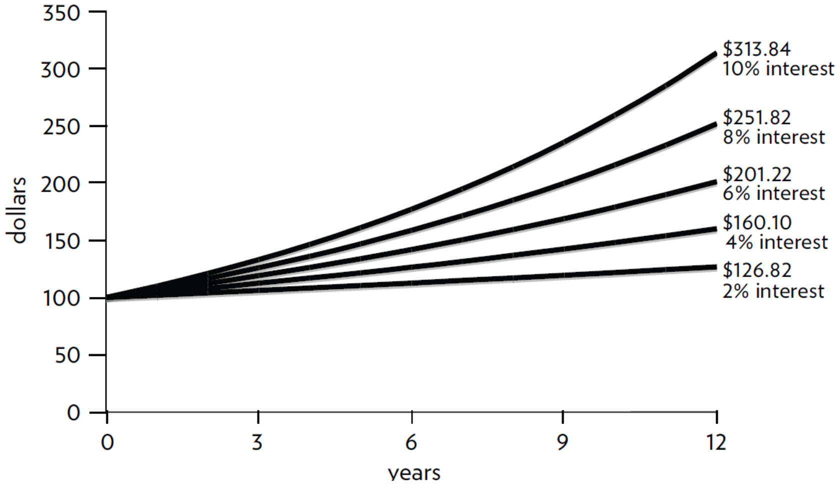
Exponential growth or decay usually indicates the presence of a reinforcing process.

- Self-amplifying or self-depleting
- Characterised by continuous acceleration or deceleration over time (nonlinear change)
- Reinforces the direction of change imposed on the system
- No inherent limits, behaviour continues until an external factor intervenes





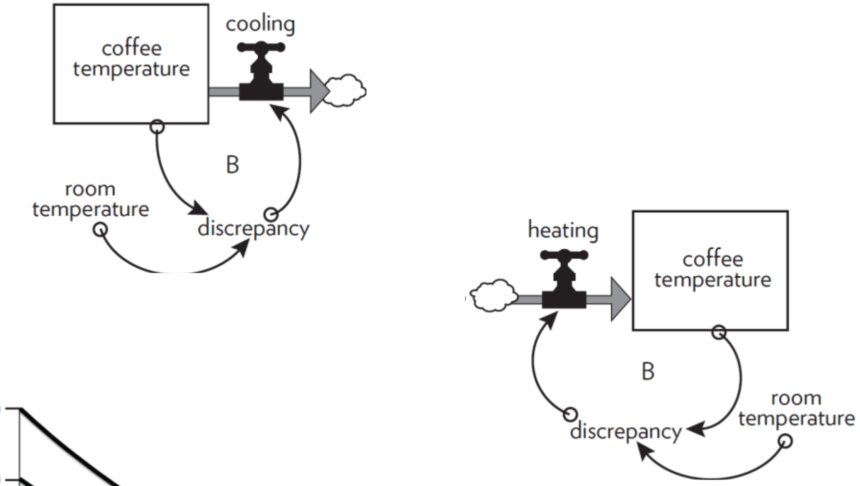


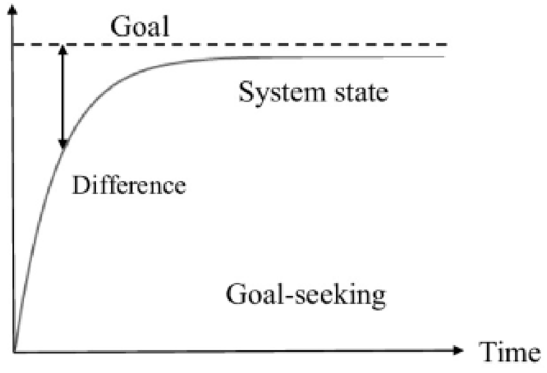


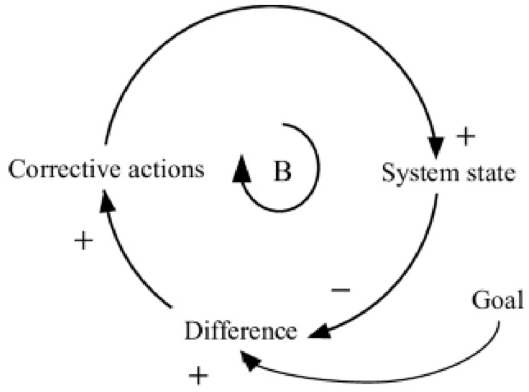
FUNDAMENTAL MODES OF DYNAMIC BEHAVIOUR

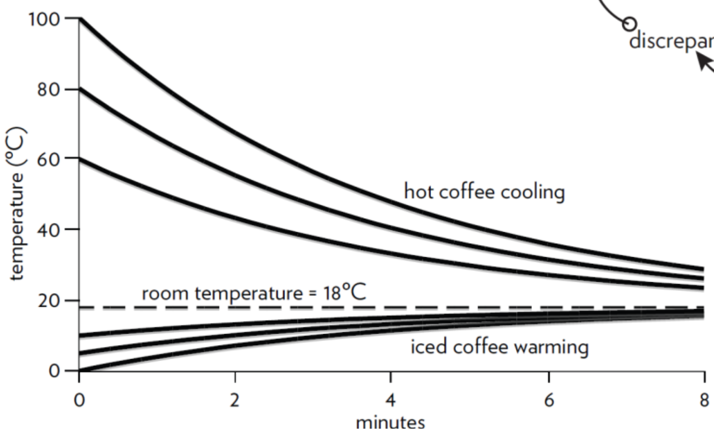
Goal-seeking behaviour is characterised by a simple balancing process, which seeks to close the gap between a goal.

- Goal or stability seeking
- process governed by a balancing feedback loop
- Adjusts system behaviour to reduce the gap between the current state and the goal





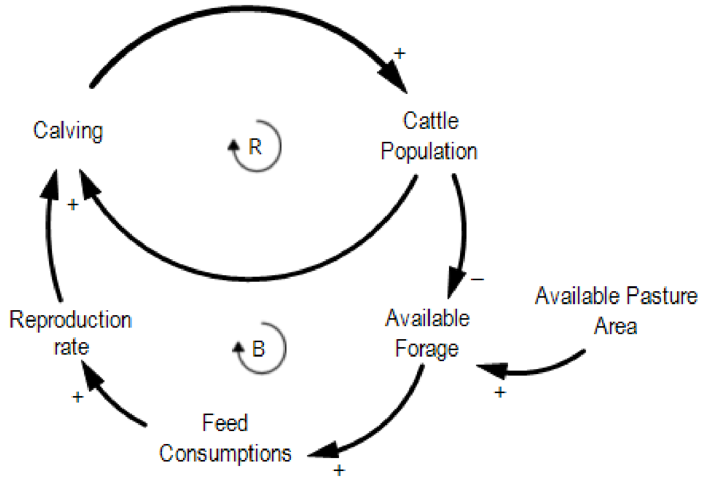


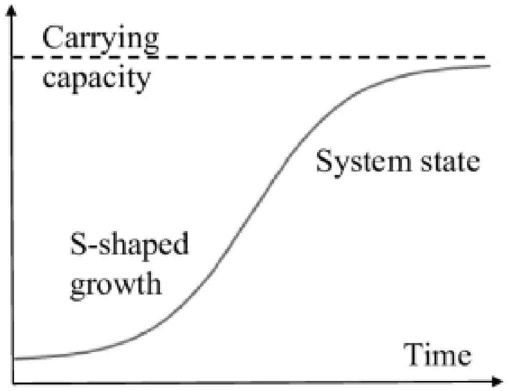


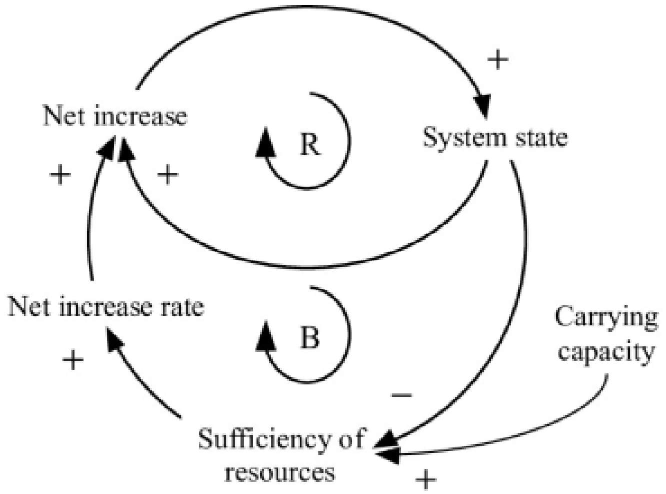
FUNDAMENTAL MODES OF DYNAMIC BEHAVIOUR

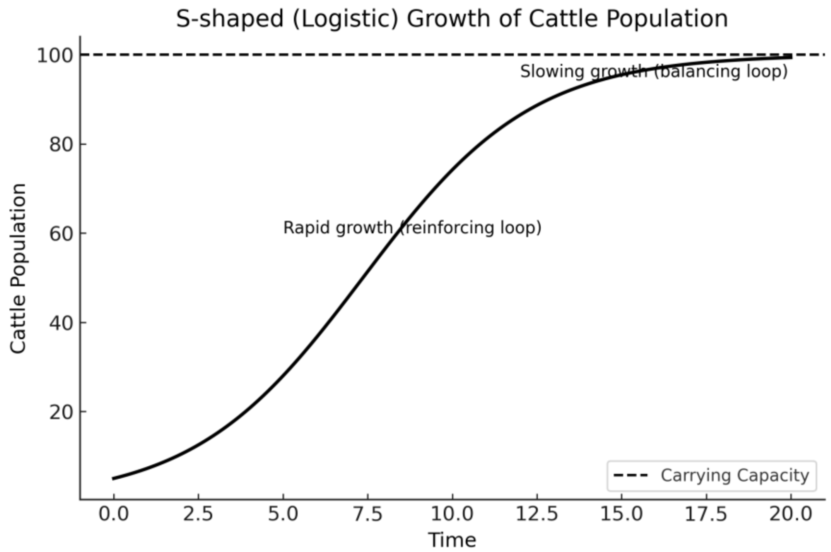
S-shaped growth is the result of a reinforcing process that has become "stalled" by a balancing process.

- Growth with limits or carrying capacity
- Initially, reinforcing, later balancing feedback dominates
- Self-regulating behaviour as the system approaches its limit
- Results in exponential growth that slows and stabilises over time





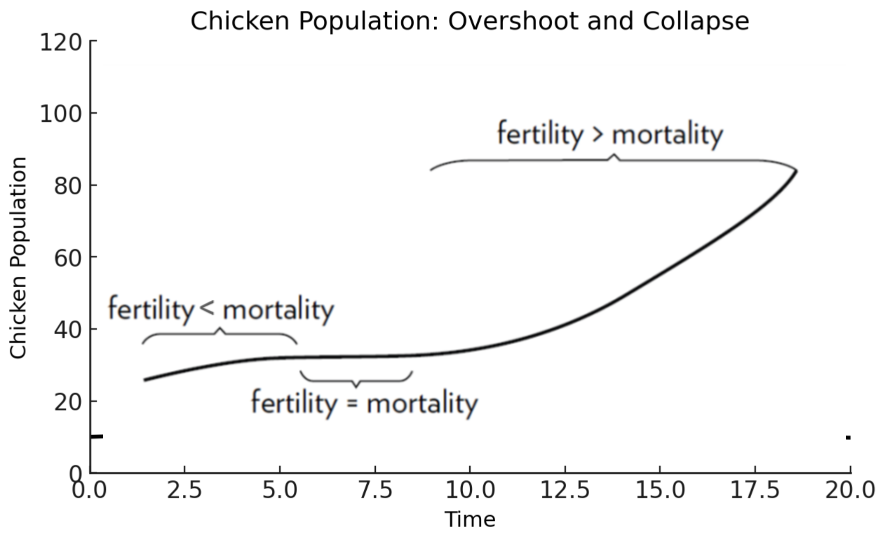


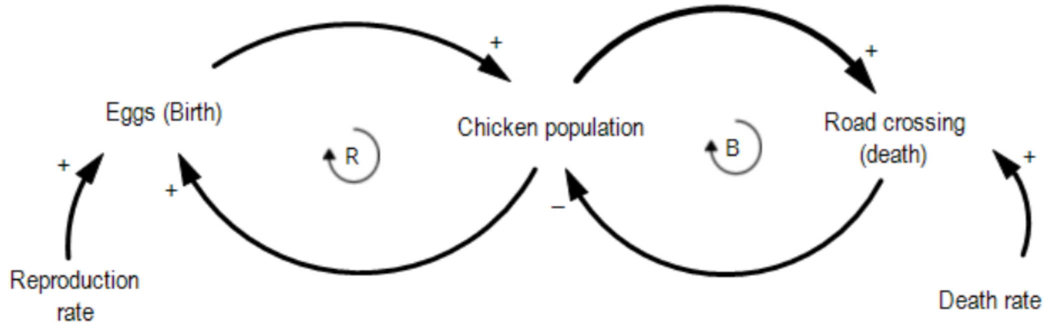


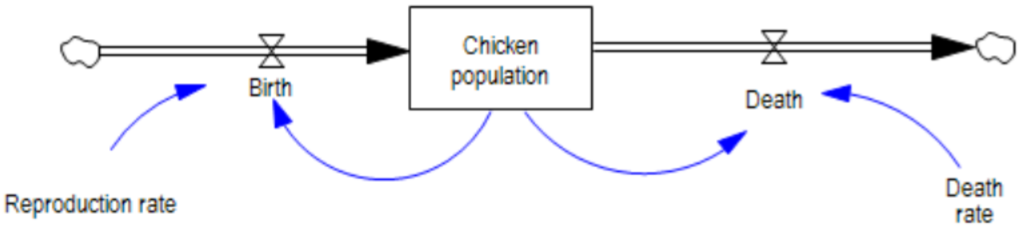
FUNDAMENTAL MODES OF DYNAMIC BEHAVIOUR

Feedback loop dominance

- When one loop dominates the other, it has a stronger impact on behaviour
- If all loops are equally strong, there is a dynamic equilibrium
- Dominance can shift over time



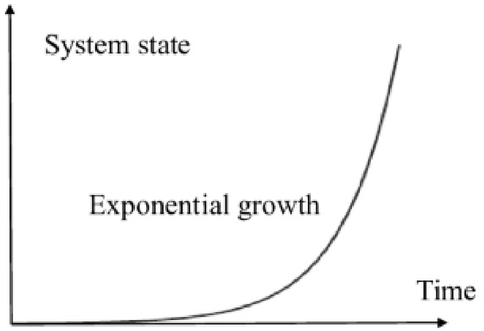


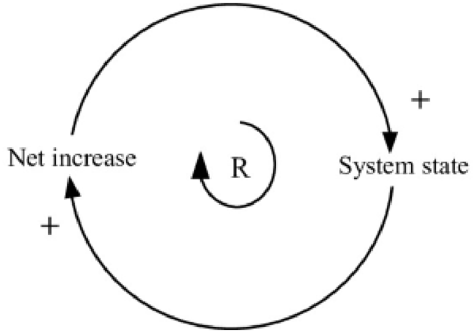


EXERCISE

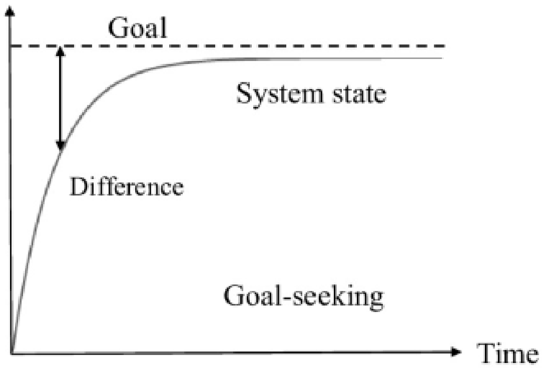
TRY to build your own CLD for each pattern (public health)

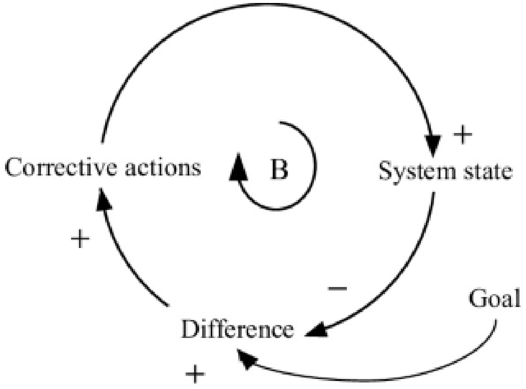
- **Exponential growth or decay**



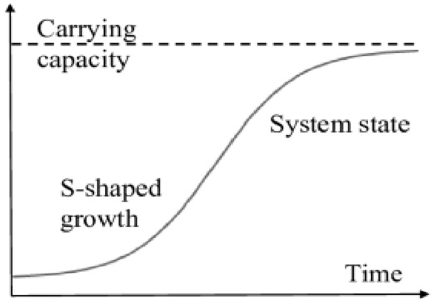


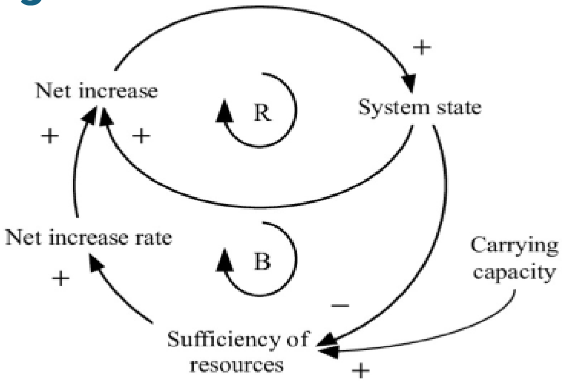
- **Goal-seeking behaviour**





- **S-shaped growth**





Ref: Williams, B., & Hummel brunner, R. (2010). Systems concepts in action: a practitioner's toolkit. Stanford University Press.

EXAMPLE (1)*

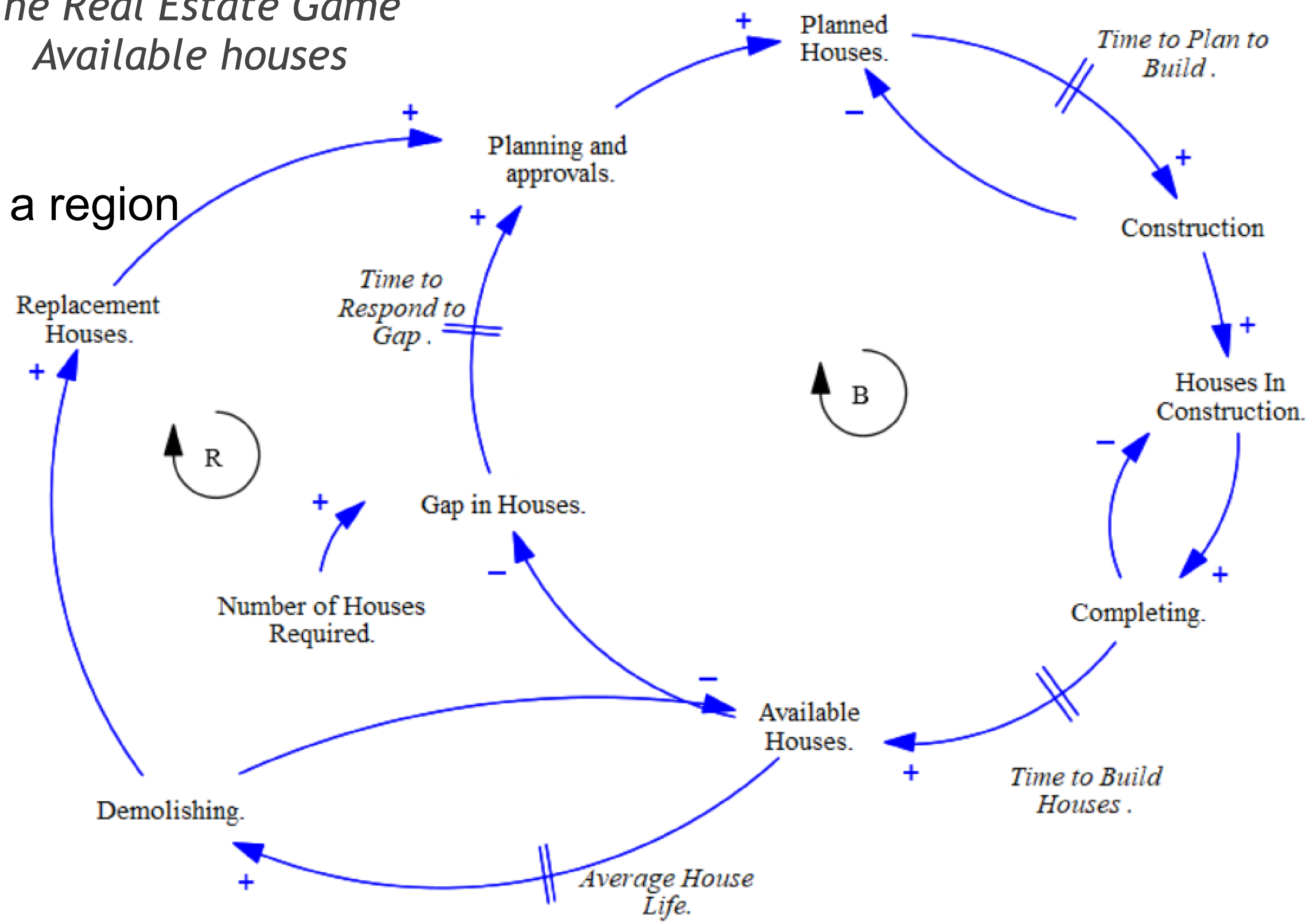
The Real Estate Game
Available houses

1. Problem Definition:

To simulate ***the available houses*** within a region in the next 100 months.

2. Problem Understanding and Qualitative Analysis

3. Stock and Flow diagramming



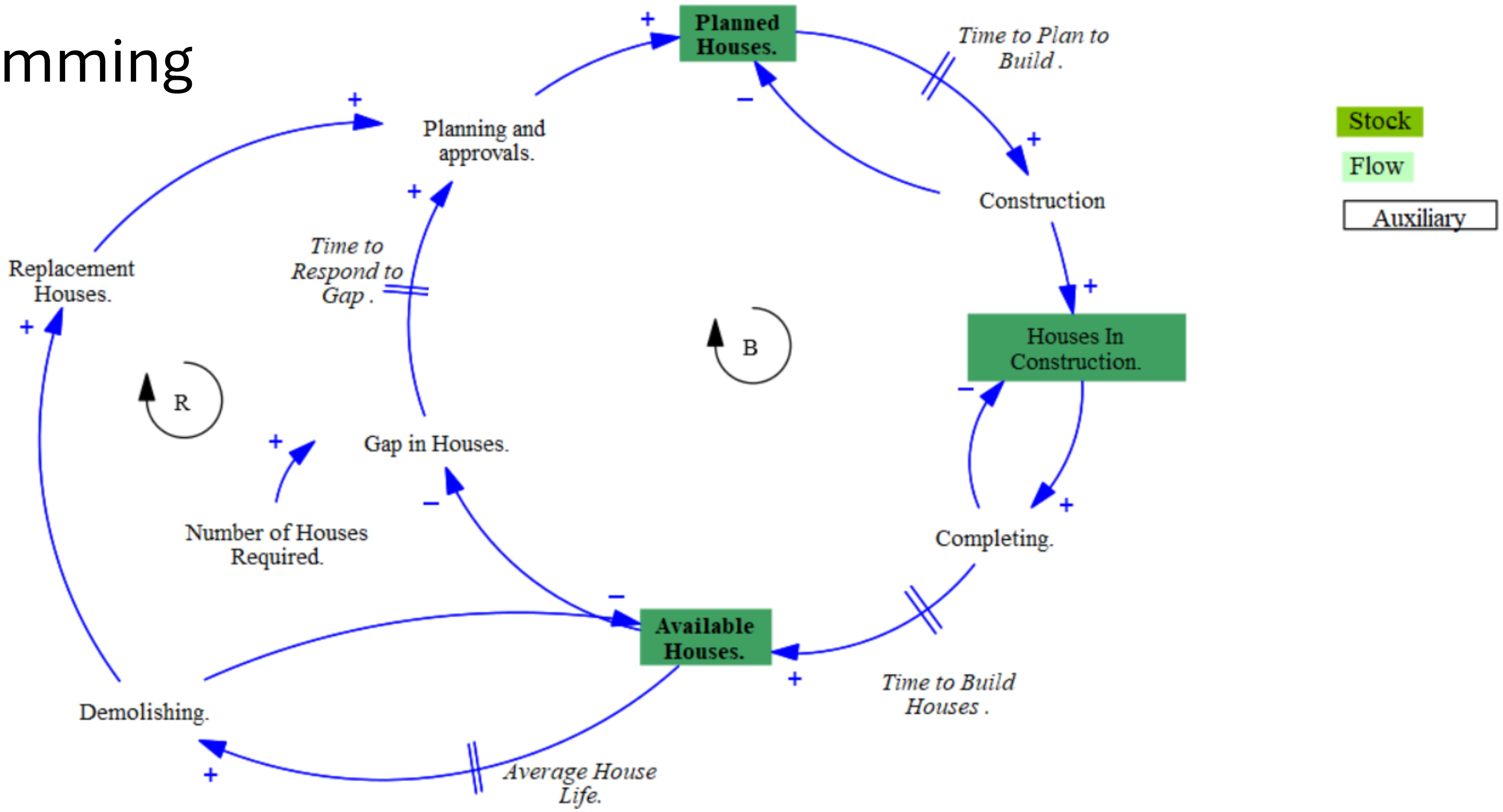
Causal Loop Diagram

* https://www.vensim.com/documentation/20760.html

EXAMPLE (1)*

The Real Estate Game
Available houses

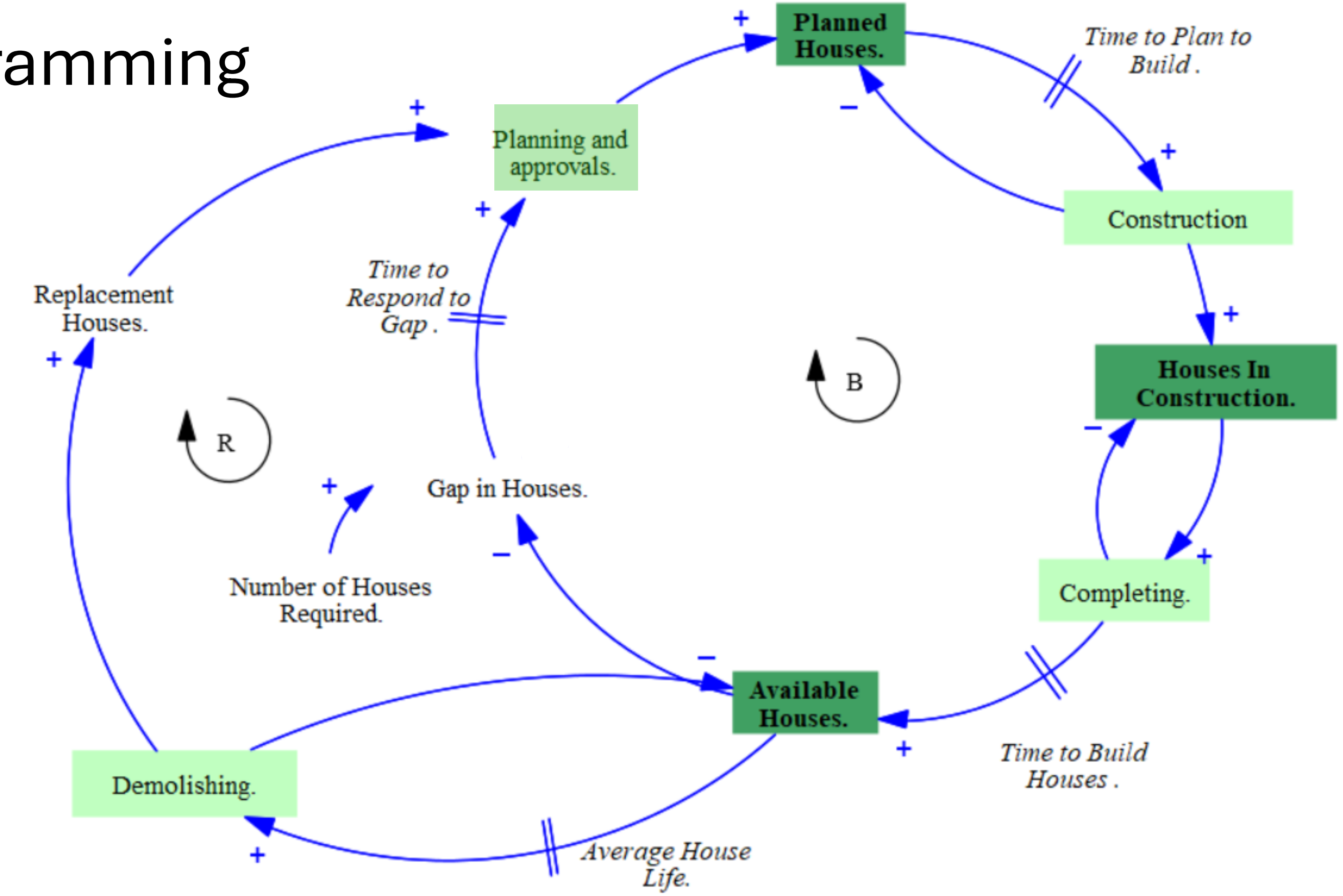
Stock and Flow diagramming

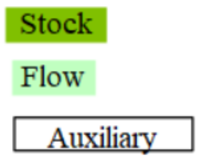


EXAMPLE (1)

The Real Estate Game
Available houses

Stock and Flow diagramming

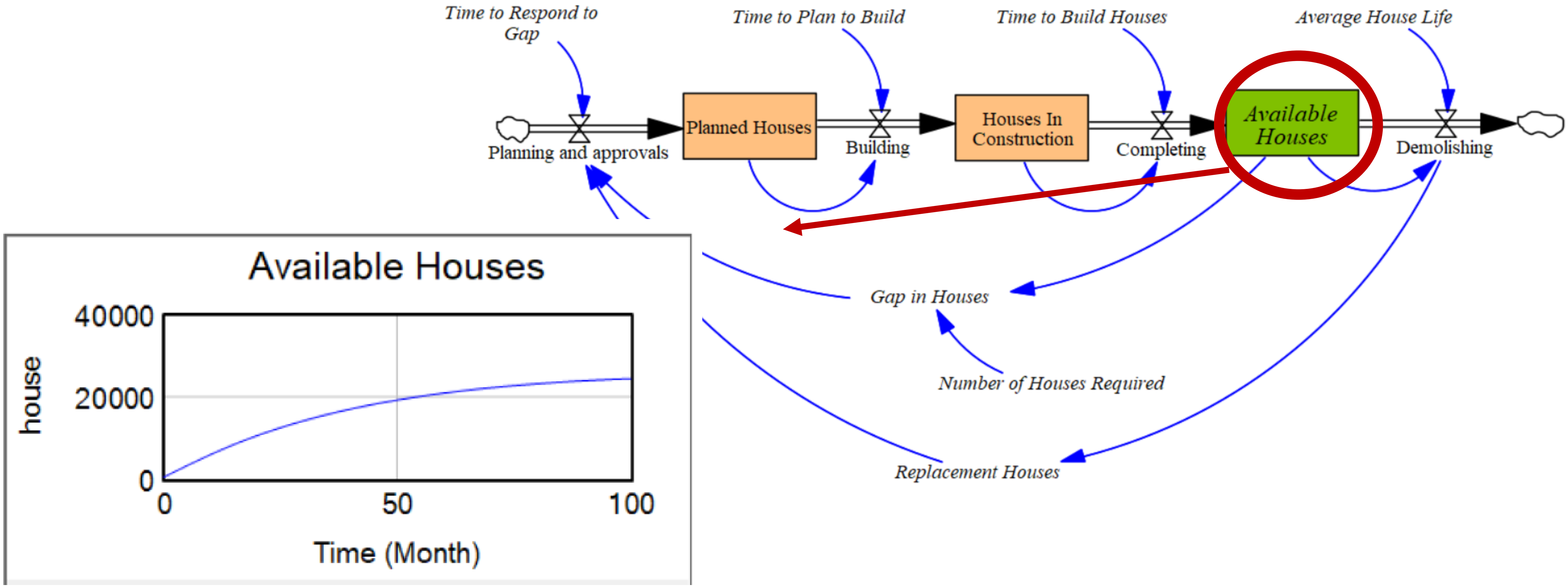




EXAMPLE (1)*

The Real Estate Game
Available houses

Stock and Flow diagramming



EXAMPLE (1)

The Real Estate Game

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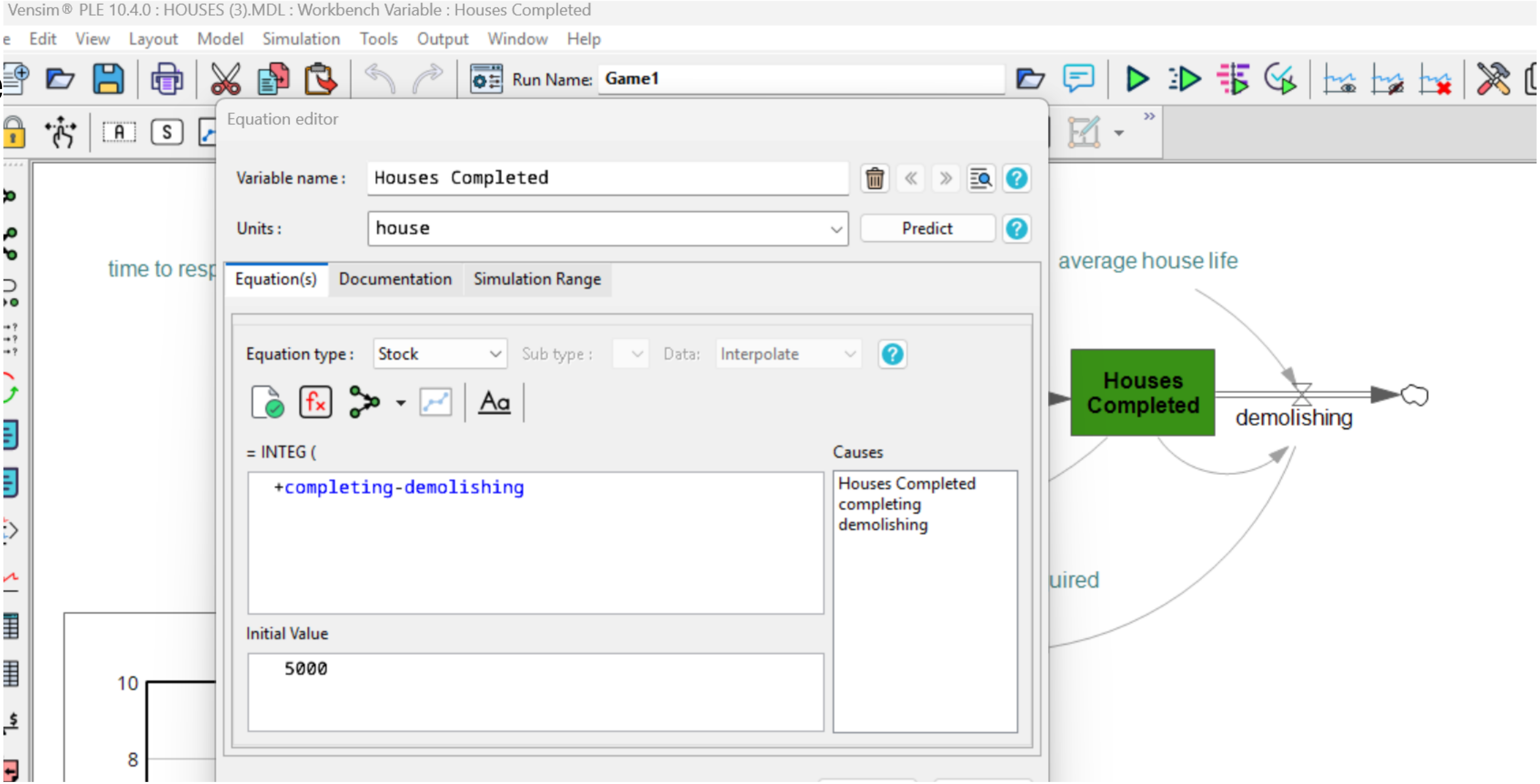
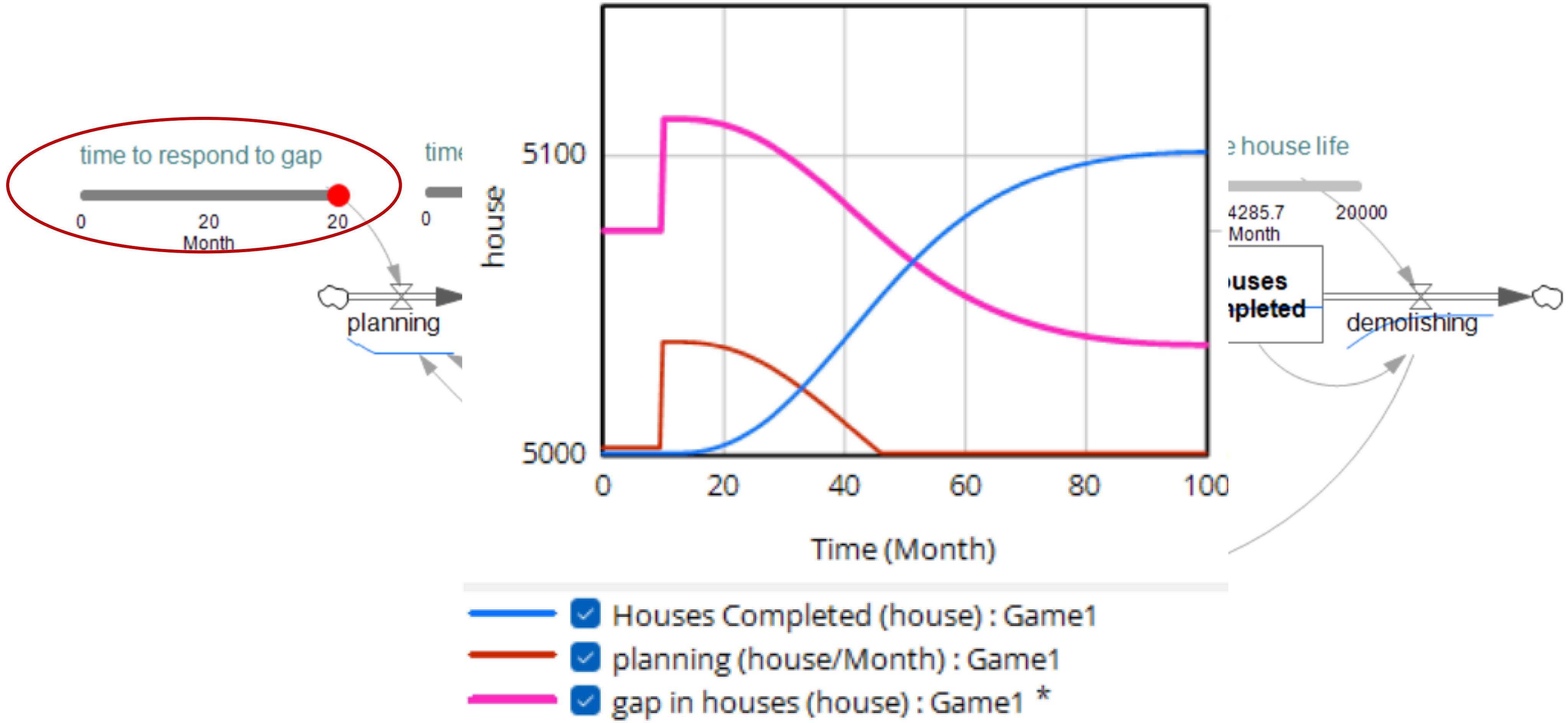


EXAMPLE (1)*

The Real Estate Game
Available houses

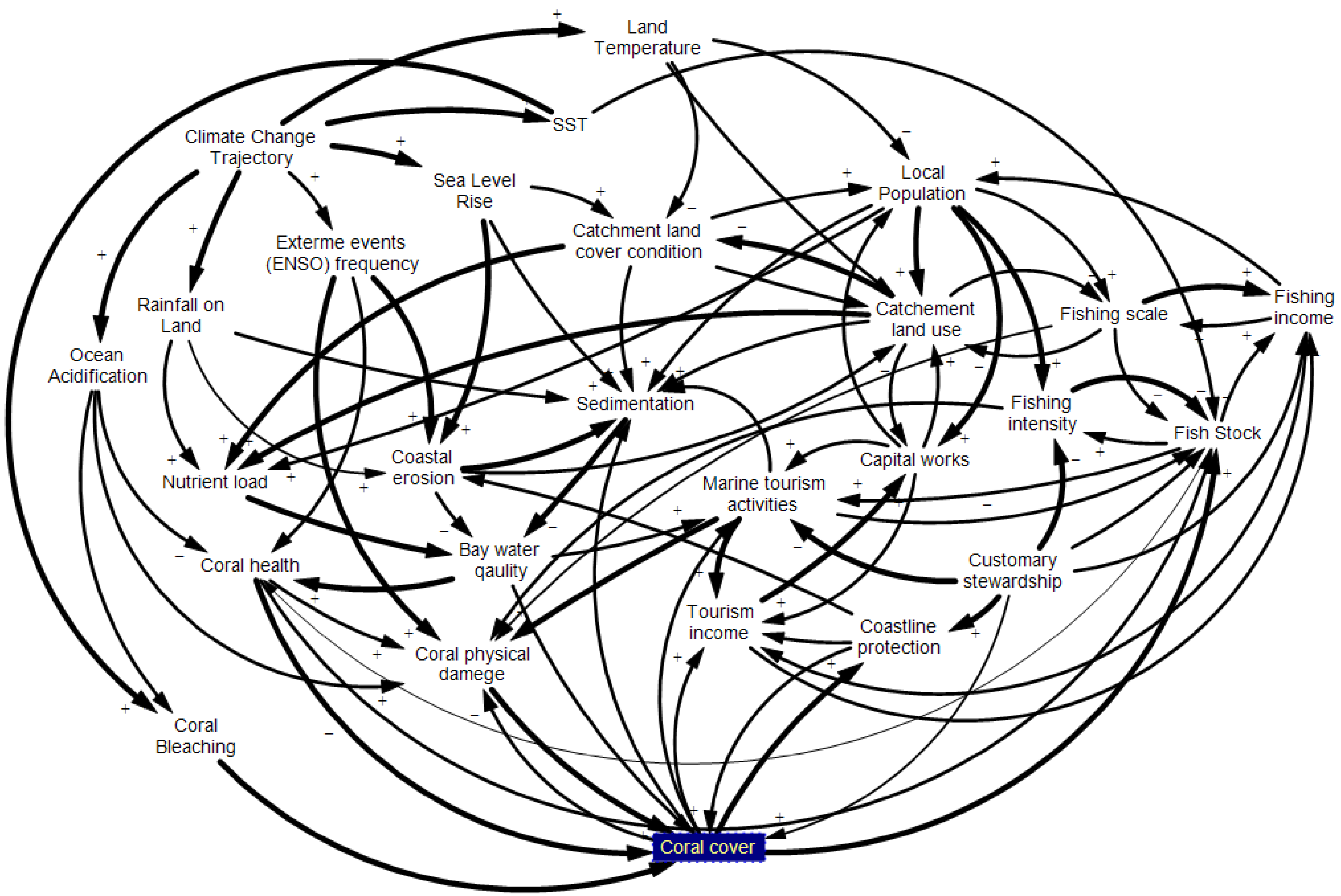
Vensim Software Simulation



Real-world Example

REAL-WORLD EXAMPLE*

System Dynamics
CLD



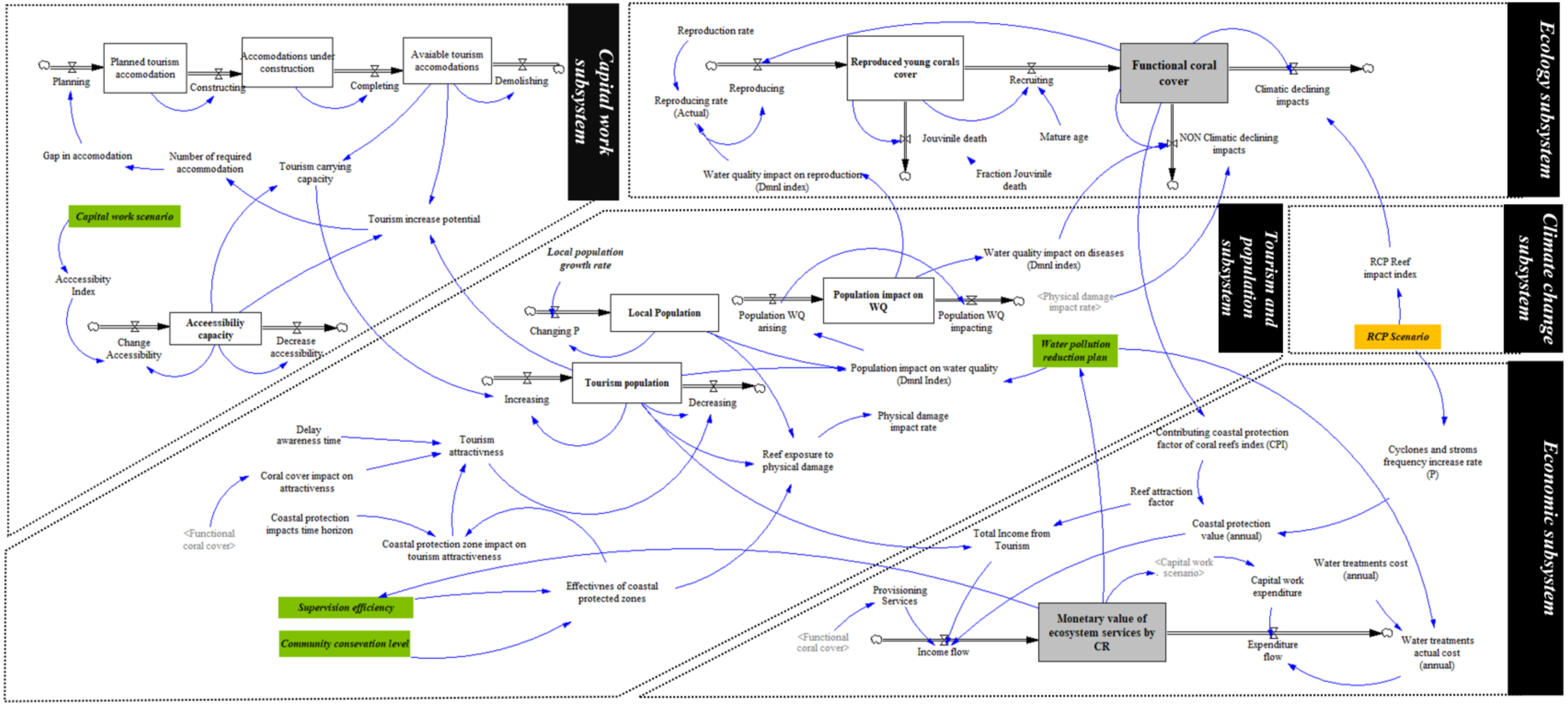
Evaluate how coral reef ecosystem services respond to climate change and management interventions, with the goal of empowering local communities of small island developing states (SIDS).

Republic of Vanuatu

Pacific EcoAdapt

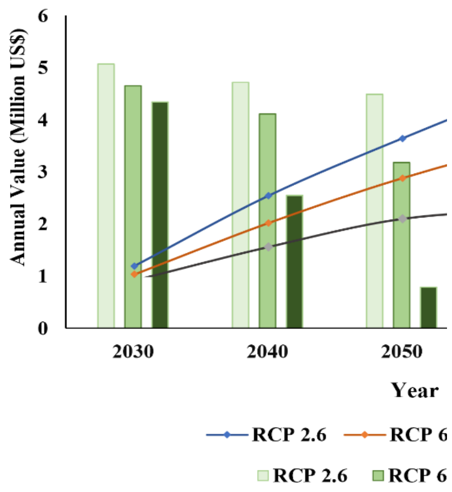
REAL-WORLD EXAMPLE*

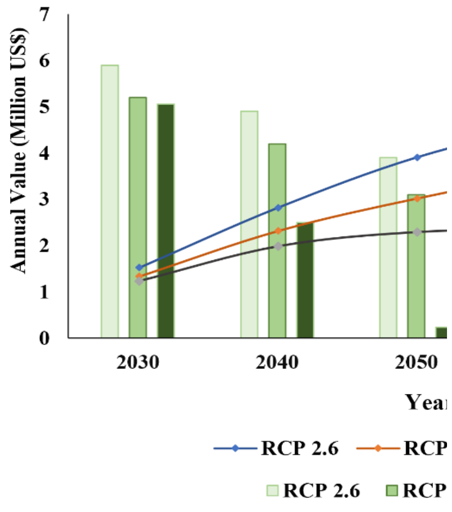
System Dynamics Simulation SFD



Pacific EcoAdapt

REAL-WORLD EXAMPLE





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ELSEVIER

Research article

Evaluating coral reef ecosystem services outcomes from climate change adaptation strategies using integrative system dynamics

Mehdi Hafezi [a,b], Rodney A. Stewart [a,b,*], Oz Sahin [a,b,c], Alyssa L. Giffin [d], Brendan Mackey [e]

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[b] Cities Research Institute, Griffith University, Nathan, QLD, 4111, Australia
[c] Griffith Climate Change Response Program, Griffith University, Southport, QLD, 4222, Australia
[d] Australian Rivers Institute - School of Science and Environment, Griffith University, Southport, QLD, 4222, Australia
[e] Griffith Climate Action Beacon, Griffith University, Southport, QLD, 4222, Australia

ARTICLE INFO

Keywords:
Systems dynamics (SD)
Bayesian networks (BN)
Structural analysis
Ecosystem services valuation
Anthropogenic pressures
Ecosystem-based management

ABSTRACT

Coral reef ecosystems provide a broad spectrum of essential ecological, economic and cultural services for Small Island Developing State (SIDS) communities. However, coral reef communities are increasingly threatened by the adverse impacts of human activities at both global and local scales. This study aims to develop an integrated dynamic assessment framework to evaluate coral reef conditions under different adaptation and climate change scenarios, and their consequential economic impacts in the small island community of Port Resolution on Tanna Island in Vanuatu. Our assessment framework follows a sequential multilayered modelling approach that uses System Dynamics (SD) coupled with Bayesian Network (BN) modelling to deal with the complexity and dynamicity of socioeconomic and environmental systems, and impacts from trans-discipline variables. The BN incorporated existing data and expert knowledge to project the future conditions of coral reefs under different scenario settings, and to parametrise and quantify the SD model where the existing data and information was insufficient. The SD was then used to simulate the dynamic relationship between coral reef condition and the economic benefits derived from its ecosystem services under different climate change (i.e. RCPs) and management scenarios through to 2070. Our findings show that sustainable community-based conservation management

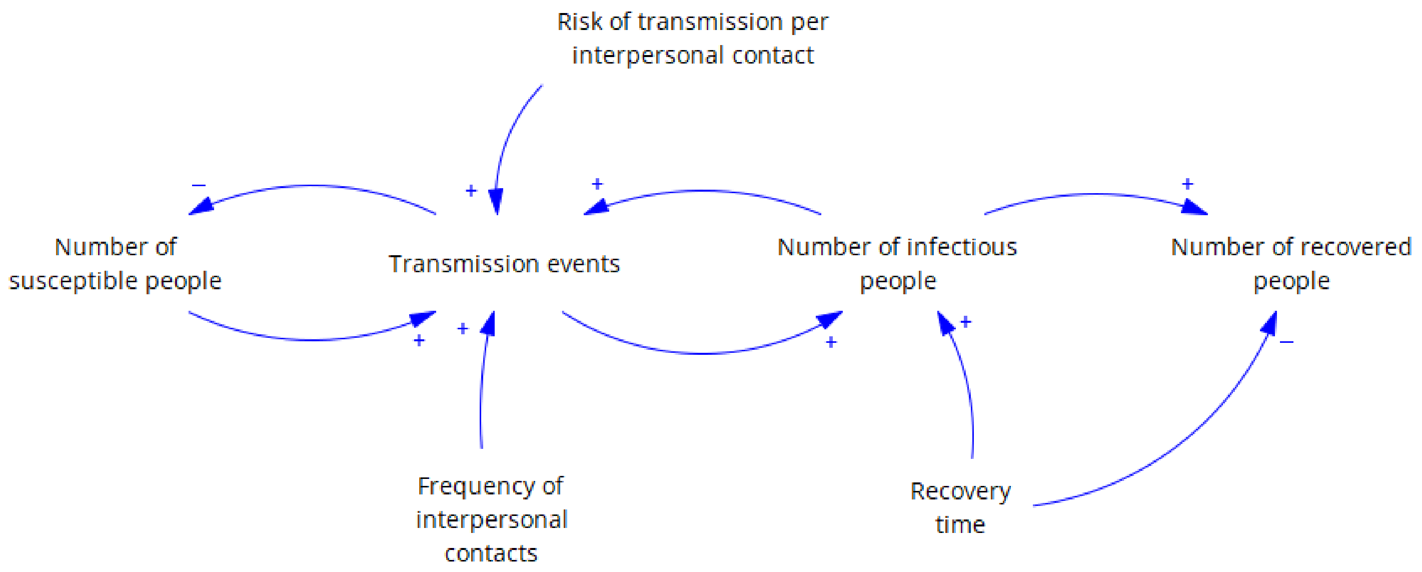
Business As Usual (Scn.3)

Unsustainable Intervention (Scn.4)

Demonstration of building a public health model

The model

- Spread of infection in a group of people
- **<u>S</u>**usceptible-**<u>I</u>**nfectious-**<u>R</u>**emoved (SIR) model



Access to the model

Application: https://insightmaker.com/

Model: https://insightmaker.com/insight/4SXJCLtsKdxVlX4pvfsGVu

Example #1

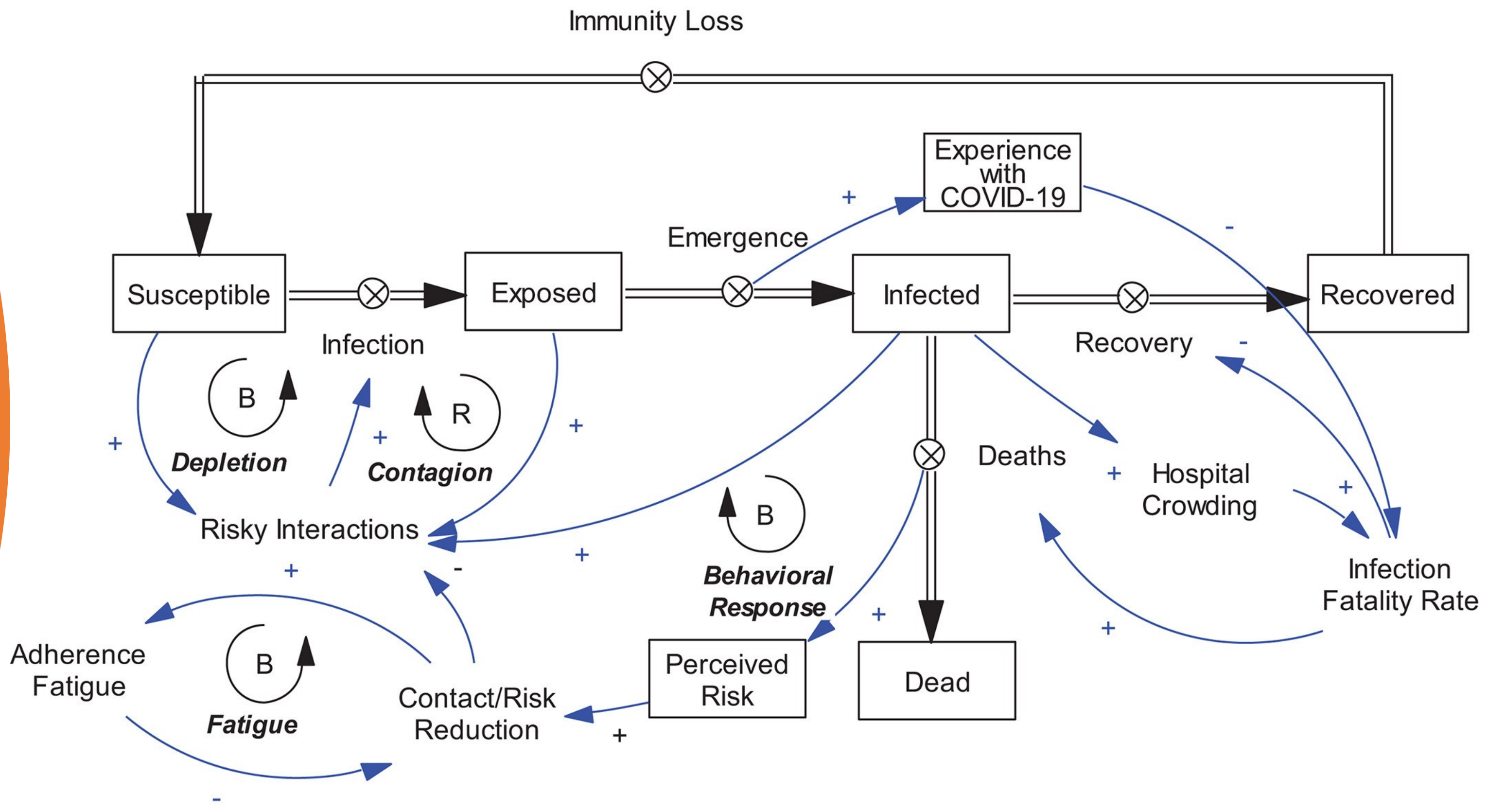
Rahmandad H, Sterman J. **Quantifying the COVID-19 endgame: is a new normal within reach?** Syst Dyn Rev. 2022 24:10.1002/sdr.1715. DOI: https://doi.org/10.1002/sdr.1715.

Objectives:

a) To project the long-term evolution of COVID-19for 93 countries, integrating biological, epidemiological, social, and behavioural factors

b) Evaluate the potential effects of policy options

The model

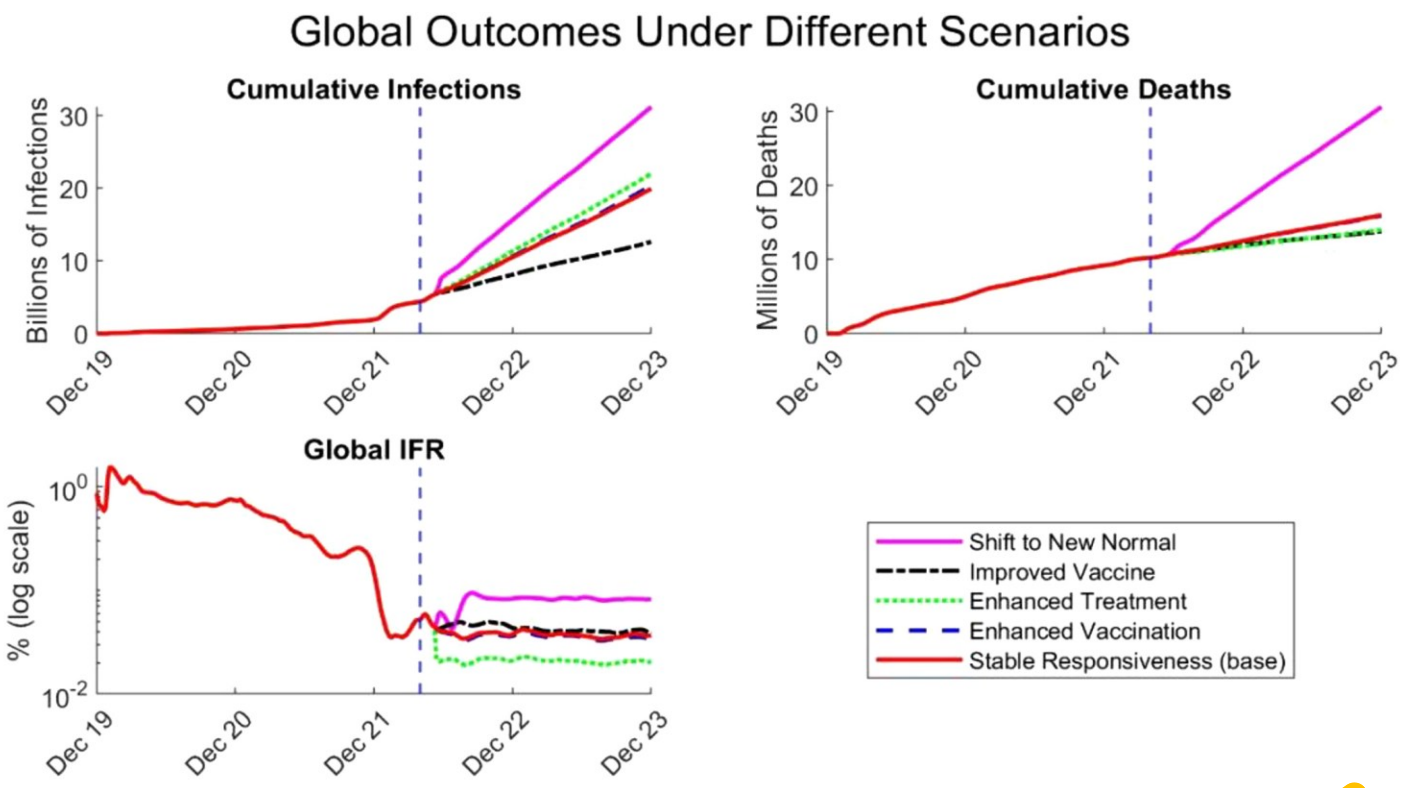


Rahmandad H, Sterman J. Quantifying the COVID-19 endgame: is a new normal within reach? Syst Dyn Rev. 2022 24:10.1002/sdr.1715

Results

Scenarios

1. Shift to a new normal: Countries adopt a new normal with reduced responsiveness, meaning perceived risk has only half the impact on interactions compared to historical responsiveness in the first 2 years of the pandemic.
2. Improved vaccines: We assume a new vaccine that restores effectiveness against transmission to 90 percent becomes globally available starting in mid-2022 and is quickly administered to all those adopting vaccines.
3. Enhanced treatment: We assume a new treatment that cuts the infection fatality rate (IFR) in half becomes globally available in the middle of 2022.
4. Enhanced vaccination: We assume that in 2022 the uptake of current vaccines increases enough to reduce the unvaccinated population by half. Vaccine efficacy is assumed to remain constant.



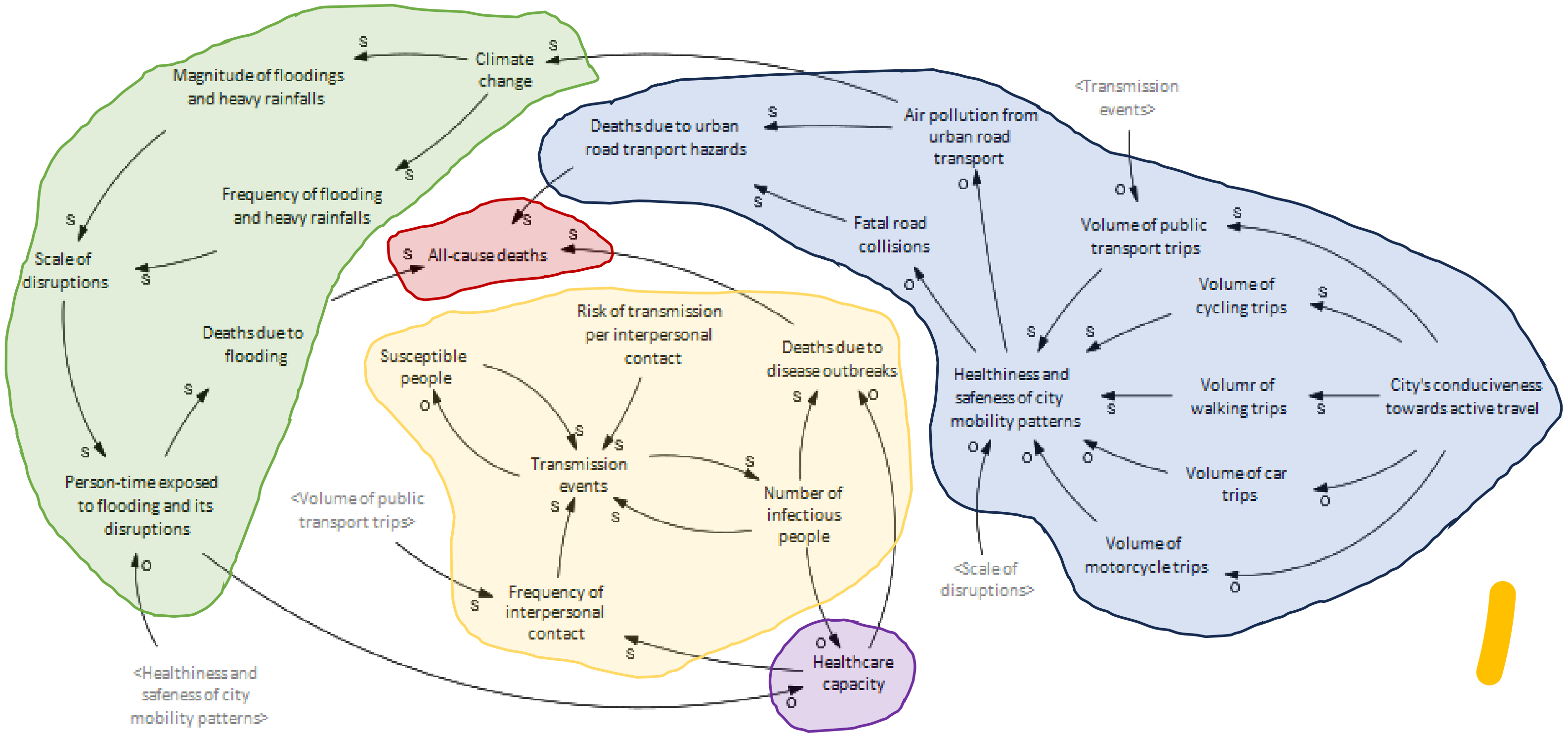
Rahmandad H, Sterman J. Quantifying the COVID-19 endgame: is a new normal within reach? Syst Dyn Rev. 2022 24:10.1002/sdr.1715

Example #2

Garcia L, Hafezi M, Lima L et al. **Future-proofing cities against negative city mobility and public health impacts of impending natural hazards: a system dynamics modelling study**. Lancet Planet Health. 2025;9(3):e207-18. DOI: https://doi.org/10.1016/s2542-5196(25)00026-9

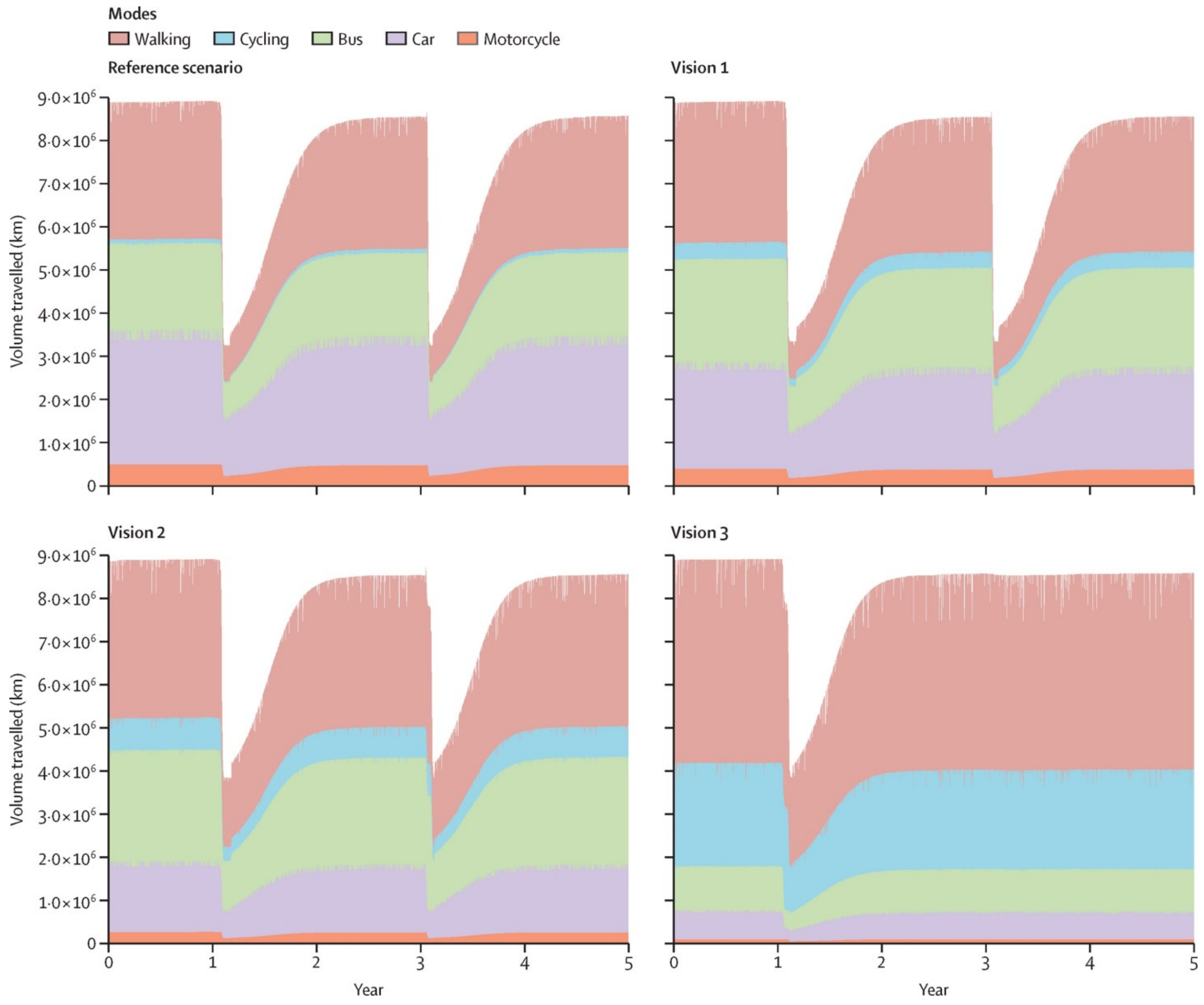
Objective: investigate how cities' transport systems, and their resulting mobility patterns, affect their capabilities to mitigate mobility and health impacts of future large-scale infectious disease outbreaks and extreme weather events.

The model



Garcia L et al. Future-proofing cities against negative city mobility and public health impacts of impending natural hazards. Lancet Planet Health. 2025;9(3):e207-18.

Results



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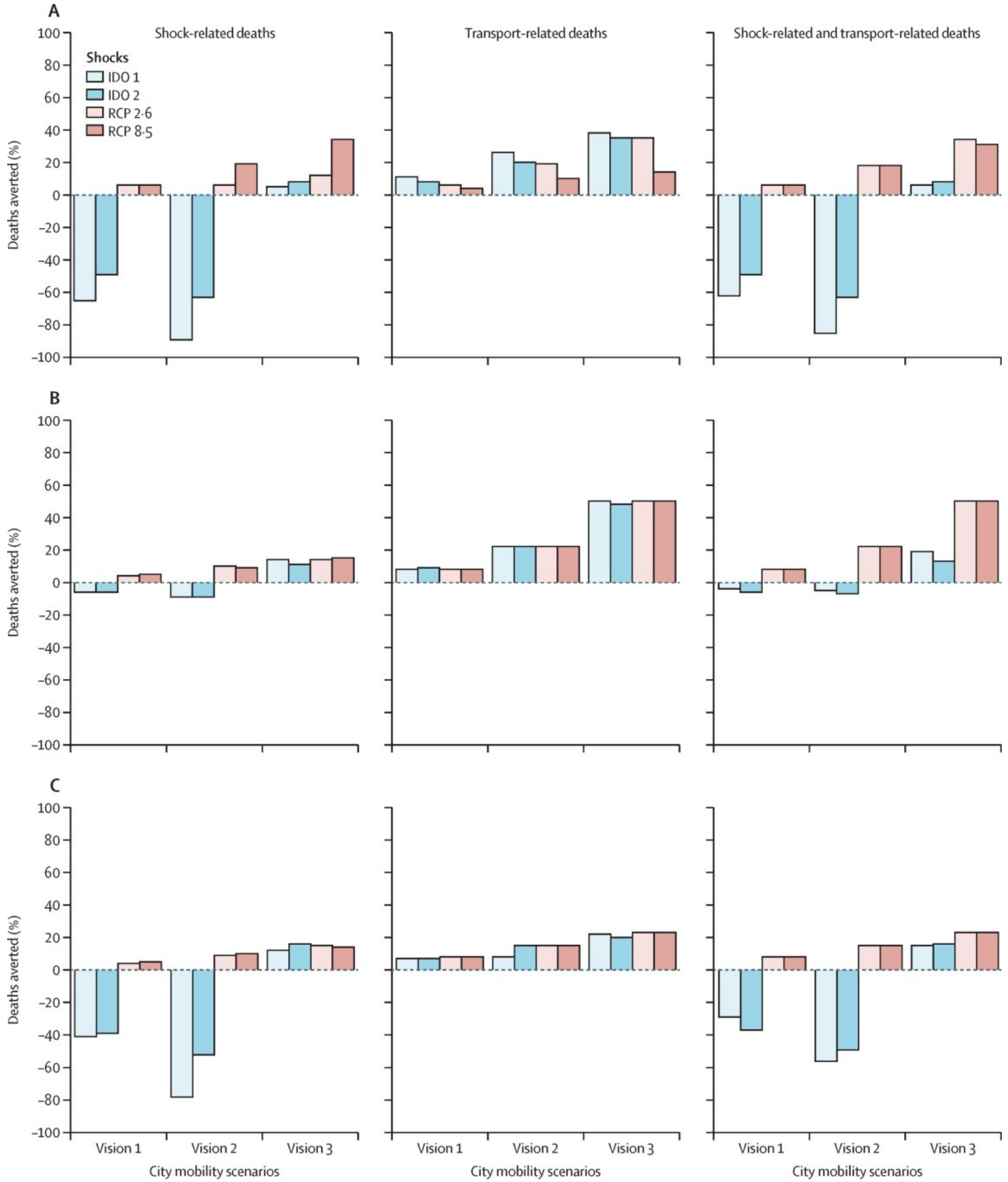
Results



Belfast

Belo Horizonte

Delhi

[Garcia L et al. Future-proofing cities against negative city mobility and public health impacts of impending natural hazards. Lancet Planet Health. 2025;9(3):e207-18.](#)

Applications to build SD simulation models

- SD software (Vensim, Stella iThink, AnyLogic)
- R and Python
- Insight Maker (https://insightmaker.com/)
- PathFwd (https://www.pathfwd.io/)

References and further support

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Short feedback survey

https://forms.office.com/e/hA97Cfz3q9

Further information

https://www.qub.ac.uk/sites/who/

Keep in touch

WHO Collaborating Centre for Research and Training on Complex Systems and Network Science for NCDs

A WHO Collaborating Centre to build capacity in systems science skills, and to formulate innovate ways to address NCDs.

https://www.linkedin.com/company/who-collaborating-centre-for-research-and-training-on-complex-systems-and-network-science-for-ncds/

COMPLEX SYSTEMS AND NETWORK SCIENCE FOR PREVENTION AND CONTROL OF NONCOMMUNICABLE DISEASES

A WHO COLLABORATING CENTRE FOR RESEARCH AND TRAINING

Member group: WHOCC for Research and Training on Complex Systems and Network Science for NCDs

Private Listed

https://www.linkedin.com/groups/13214019/

SAVE THE DATE

COMPLEX SYSTEMS AND NETWORK SCIENCE FOR PREVENTION AND CONTROL OF NONCOMMUNICABLE DISEASES

A WHO COLLABORATING CENTRE FOR RESEARCH AND TRAINING

Join us for a series of online short courses designed to build skills in a range of systems thinking methods for NCD prevention and control. Further details and registration links will be advertised 6 weeks in advance of the training sessions.

Introduction to Systems Dynamics Modelling:
Wednesday 15 & 22 October 2025 10:30 – 12:30 (BST)

Introduction to Agent-based Modelling:
Wednesday 5 & 12 November 2025 10:30 – 12:30 (GMT)

Introduction to Soft Systems Modelling:
Wednesday 21 & 28 January 2026 10:30 – 12:30 (GMT)

Introduction to Viable Systems Modelling:
Wednesday 18 & 25 February 2026 10:30 – 12:30 (GMT)

Introduction to Systems Maps and Causal Loop Diagrams:
Wednesday 25 March & Wed 1 April 2026 10:30 – 12:30 (GMT)

Introduction to Stakeholder Network Analysis:
Wednesday 22 & 29 April 2026 10:30 – 12:30 (BST)

QUEEN'S UNIVERSITY BELFAST

qub.ac.uk/sites/who

whocc@qub.ac.uk

SCAN ME

What we saw today

- Recap of session 1 (10 min) - Mehdi
- Stock and flow diagramming (20 min) - Mehdi
- Behaviour patterns (15 min) - Mehdi
- Q&A (10 min)
- Comfort break (5 min)
- Demonstration of building a public health model (20 min) - Leandro
    - Using data to inform your model (10 min) - Leandro
    - Analysing and visualising outputs (10 min) - Leandro
- Q&A (15 min)
- Closing (5 min) - Leandro

Introduction to System Dynamics Modelling – day 2

Dr Leandro Garcia, Queen's University Belfast (l.garcia@qub.ac.uk)

Dr Mehdi Hafezi, Cranfield University (Mehdi.Hafezi@cranfield.ac.uk)

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