Introduction to System Dynamics

Paweł Litwin

Rzeszów University of Technology

Co-funded by the European Union

TET - The Evolving Textbook
Project no: 2022-1-SI01-KA220-HED-000088975

Exploring System Dynamics Basics

- Introduction to System Dynamics
- Core Principles of System Dynamics
- System Structure and Interrelations
- Numerical Simulation Process
- Causal Loop Diagrams (CLD)
- Understanding Feedback Loops
- Software Tools for System Dynamics
- Variables in System Dynamics
- Accumulation in Dynamics

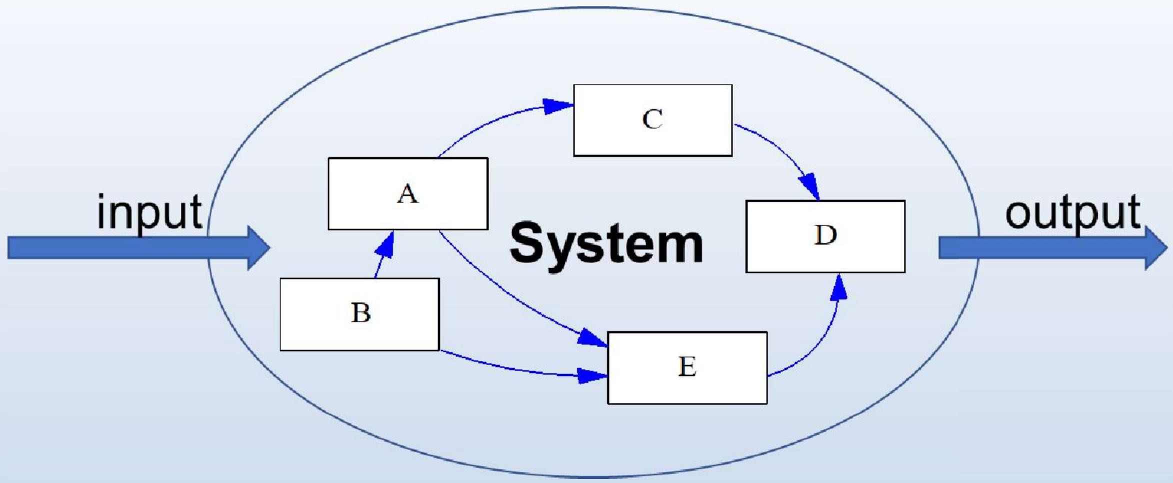
Definition of System Dynamics

- „System dynamics is a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems — literally any dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality.”
  - System Dynamics Society webpage

Definition of System

- System is a **collection of interacting components**, connected together in such a way, that the modification in one component affects the other components
- The system has **clearly defined boundaries**, which makes it clear which entities are inside the system and which are outside its boundaries - are part of the environment.
- The system is a collection of parts **created for a purpose**.

Definition of System



- **Causal** definition states that the System implements a time-dependent representation of an input signal on a time-dependent output signal

Introduction to System Dynamics

- **Continuous Simulation Methodology:** System dynamics focuses on continuous simulation to analyze behavior of dynamic systems over time.
- **Foundational Principle:** Originating from Jay W. Forrester's work, it emphasizes interdependencies and feedback loops within systems.
- **Complex System Analysis:** Essential for understanding complex systems lacking precise rules, enhancing insights into their behaviors and interactions.

Core Principles of System Dynamics

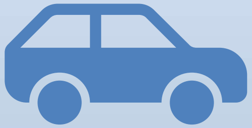
Structure-Behavior Relationship: The structure of a system defines its dynamics, influencing how different elements interact and behave.

Feedback Loop Importance: Feedback loops are crucial in shaping system behavior, stabilizing dynamics or triggering exponential changes.

Causal Relationships: Understanding causal relationships among components aids in predicting system responses to various influences.

Applications of System Dynamics

Aerospace Applications: System dynamics aids in optimizing flight operations, resource management, and supply chain dynamics in aerospace.



Automotive Industry Modeling: In automotive sectors, system dynamics improves production efficiency and manages supply chain complexities effectively.

Energy Sector Simulation: Energy systems utilize system dynamics for modeling demand responses and regulatory impacts on generation and distribution.

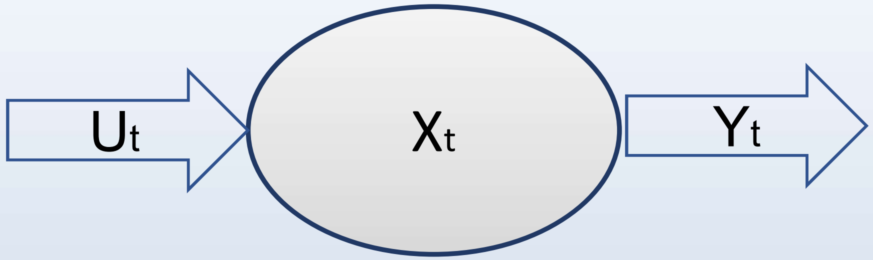
Static and Dynamic Systems

- In **Static System** the output depends only on the current input and does not change with time if the input is time-invariant.
- In **Dynamic System** *output depends on the current and the previous input*. The output changes in time, even if the input is constant.
- For a system to be dynamic, it must have the memory..

What makes system dynamic?

- Input signals do not change over time.
- System behavior changes over time.
- …it must have the memory!.

Variables in System Dynamics



- **Input Variables:** Input variables (U(t)) represent external factors affecting the system, such as supply levels and customer demands.
- **Output Variables:** Output variables (Y(t)) signify the outcomes of system behaviors, like production rates and sales figures derived from inputs.
- **State Variables:** State variables (X(t)) capture historical data reflecting the status of inputs and outputs over time in the system.

State variables are a record of the history of the system.

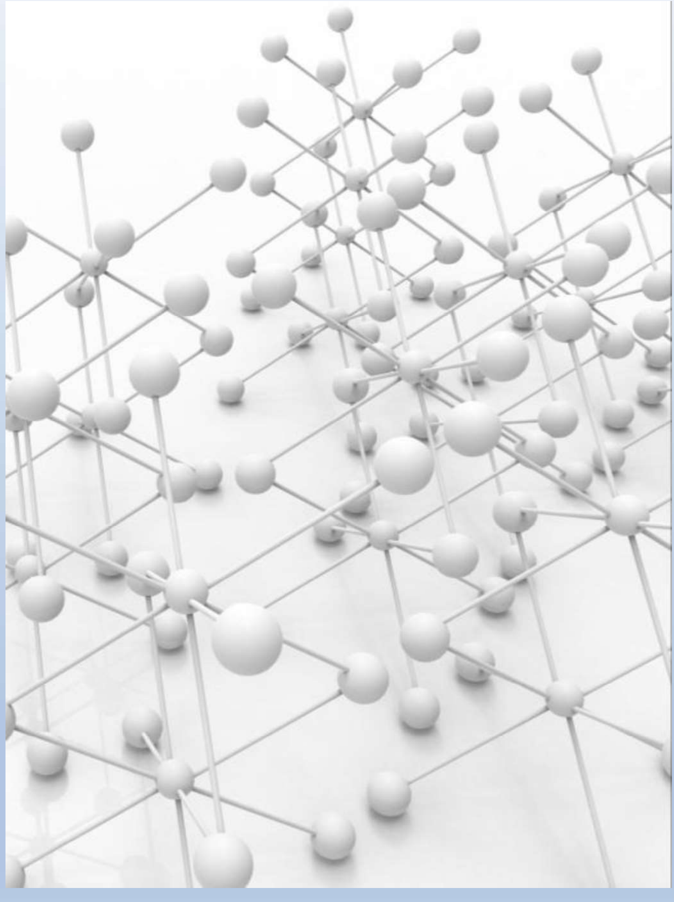
$$x_t = \int (u_t - y_t) \cdot dt + C$$

Contributions of Jay W. Forrester

- **Forrester's Supply Chain Model:** Forrester developed a simplified supply chain model featuring key components such as producers and retailers.
- **Key Flow Elements:** The model includes essential flows: orders, information, materials, and inventory management to enhance understanding.
- **Interconnected System Dynamics:** Forrester's model illustrates the interplay among producers, distributors, and retailers, highlighting dynamic interdependencies.

System Structure and Interrelations

- **Structural Influence on Behavior:** The system's structure inherently influences the interactions between its components, determining overall behavior dynamics.
- **Interdependencies and Feedbacks:** Interrelationships shaped by system structure create feedback loops that crucially impact performance and stability.
- **Dynamic Response Variation:** Changes in structural configuration modulate how systems respond to external stimuli, affecting system adaptability.



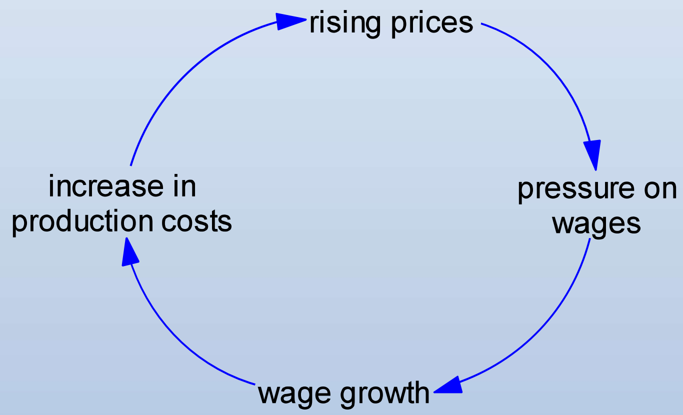
Cause and Effect Understanding

Causal thinking is the key to organizing ideas in a system dynamics study.

Examples are:

tired → sleep,

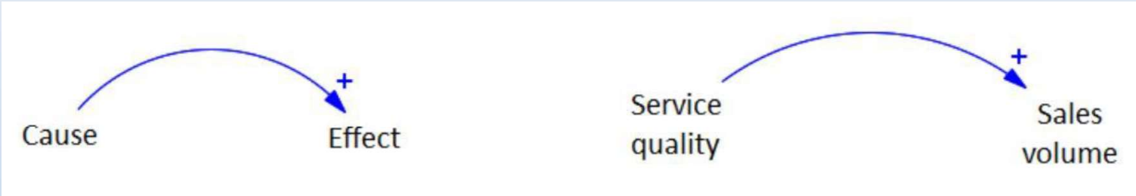
hungry → eat,



rising prices → pressure on wages →
wage growth → increase in production costs → rising prices.

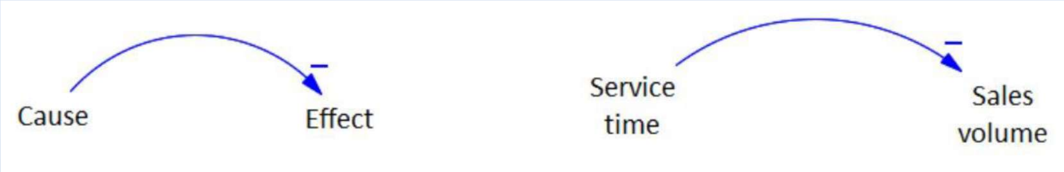
- Causal relationships are positive (+) or negative (-)

Positive causal relations



- The positive relationship means that an increase in the value of the cause, leads to an increase in the effect above the state, achieved without an increase in the cause.
- Conversely, decreasing the value of the cause leads to a decrease in the effect below the value achieved without decreasing the value of the cause.

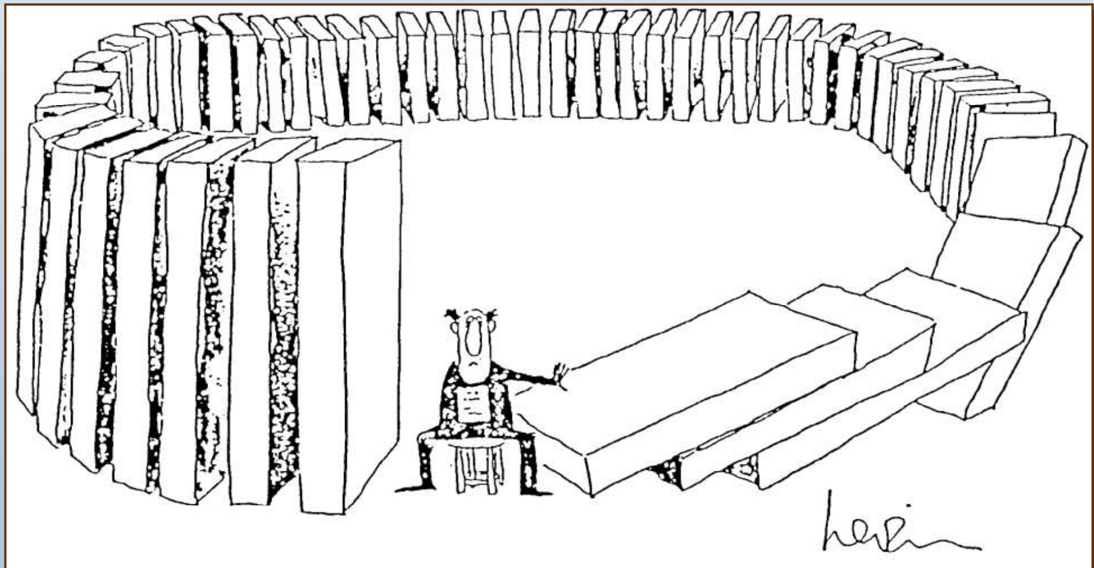
Negative causal relations



- A negative cause-effect relationship, on the other hand, indicates that for an increase in the value of the cause, the value of the effect decreases below the level that would have been achieved without the increase in the value of the cause. For a decrease in the value of the cause, the value of the effect increases above the level that would have been achieved without the decrease in the cause.

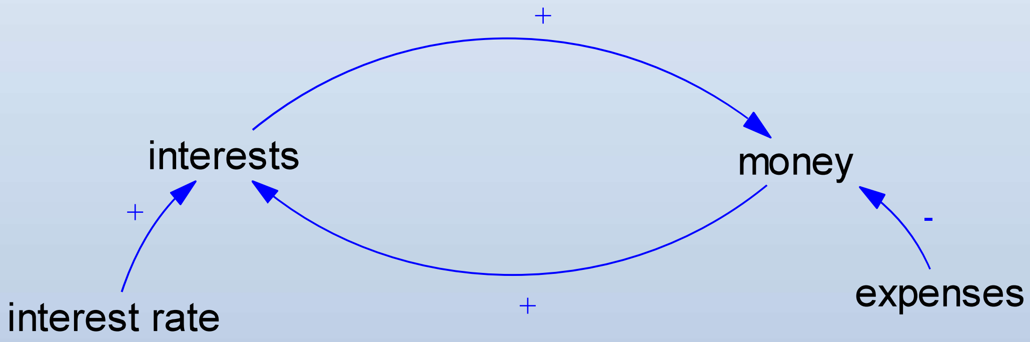
Feedback loop

Feedback loop occurs when an initial cause ripples through a chain of causation ultimately to re-affect itself.



Drawing by Levin; © 1976 The New Yorker Magazine, Inc.

Sample Causal Loop Diagram



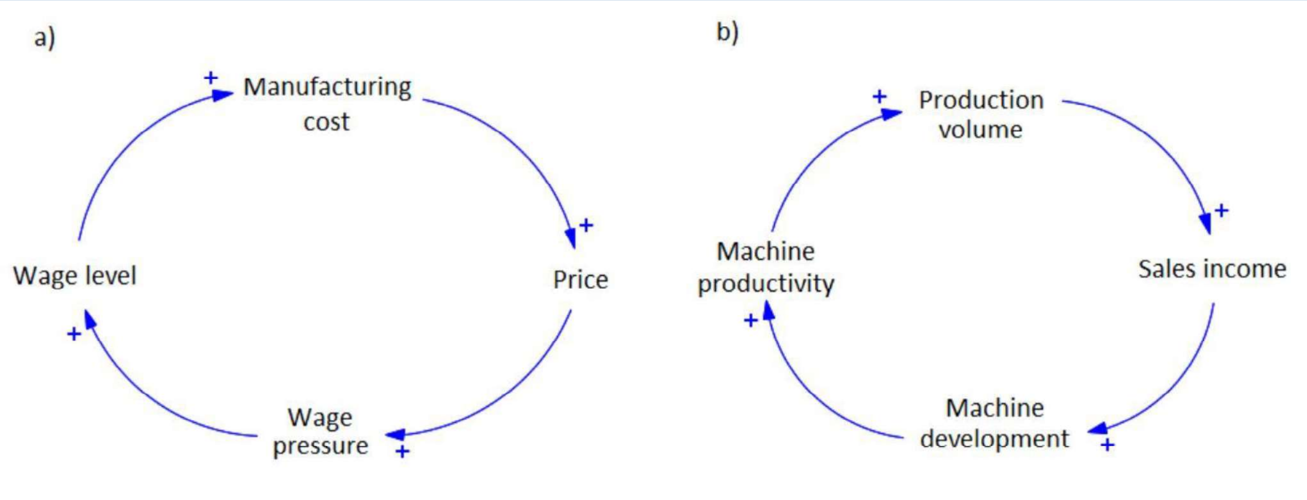
Reinforcing loop

Understanding Feedback Loops

- **Reinforcing Loops:** Reinforcing loops amplify changes in a system, leading to growth or decline, evident in population dynamics.
- **Balancing Loops:** Balancing loops work to stabilize a system by counteracting deviations, exemplified by thermostat temperature control.
- **Real-World Implications:** Understanding these loops enhances strategic decision-making across diverse fields like economics and ecology.

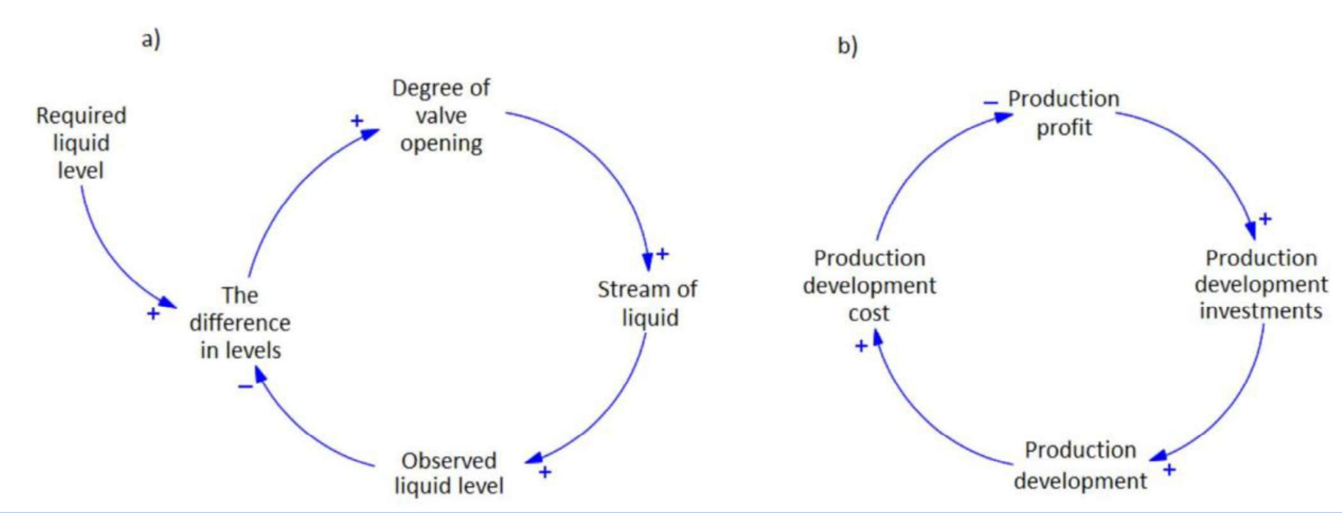
Positive feedback loop

A positive feedback loop with respect to a particular element of the system indicates that a change in its characteristics triggers a new change in the same direction after some time. The inflation model, for example, results from positive causal relationships between the cost of production and the price of the product, the pressure on wages and their amount affecting the cost of production (fig. a). Another example is the model of increased productivity of machinery, as a result of positive causal relationships between the volume of production and sales revenue and investment in machinery development (fig. b).



Negative feedback loop

A negative feedback loop, on the other hand, arises when a change in the characteristics of a system component is offset by an action that produces the opposite effect to the change. This type of loop is referred to as “stabilizing feedback”. A stabilizing feedback loop includes an autocorrection mechanism to produce a specific signal value. An example of a stabilizing feedback loop with a fixed level that the system strives for is the process of filling a tank with liquid. The degree of opening of the valve positively affects the flow rate of liquid entering the tank. A positive cause-and-effect relationship also exists between the flow rate of the liquid and the instantaneous level of the liquid in the tank.



Labeling of feedback loops

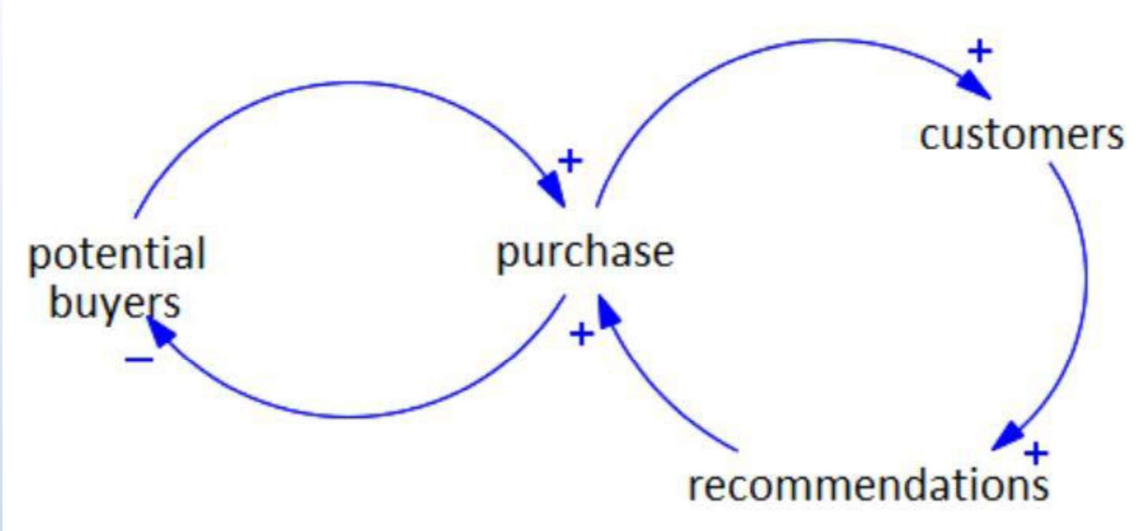
When the number of negative cause-effect relationships is even then the loop under consideration is positive. An odd number of negative cause-effect relationships indicates that the loop is negative.

Labeling of feedback loops: a) positive and b) negative.
R - positive loop (reinforcing loop), B - negative loop (balancing loop).

Combining Feedback Loops

- **Mixed Systems Defined:** Mixed systems integrate multiple feedback structures, influencing dynamic behaviors through intertwined causal relationships.
- **Customer Acquisition Model:** This model showcases customer growth dynamics, illustrating interplay between marketing efforts and customer responses.
- **Feedback Structures Interaction:** Different feedback loops within mixed systems can create complex interactions, impacting overall system performance dynamically.

Mixed loop behaviour



In the customer acquisition model, the number of new purchases is proportional to the number of potential buyers and the number of product recommendations given by customers. In the first stage, the increase in the number of customers is exponential - the number of recommendations and purchases increases rapidly. In the second phase of the analysis of the considered model, as a result of the decrease in the number of potential buyers, there is a decrease in the number of customers acquired. In addition, the completion of purchases by all potential buyers causes the system to enter a phase of stabilization

Examples of Feedback in Real-World Systems

- **Positive Feedback Example:** Population growth exemplifies positive feedback, where increased individuals lead to more births, further accelerating growth.
- **Negative Feedback Instance:** Thermostat systems illustrate negative feedback; temperature deviations trigger actions to maintain a stable climate environment.
- **Implications of Feedback Loops:** Understanding feedback loops enhances strategic planning, influencing resource management and operational responses in diverse sectors.

Insights from Causal Loop Diagrams

- **Insights from Causal Loop Diagrams:** Causal Loop Diagrams illuminate complex interdependencies, aiding identification of system behavior issues and feedback effects.
- **Highlighting System Disruptions:** CLDs can pinpoint potential disruptions by revealing cyclical patterns that may lead to undesirable system dynamics.
- **Influencing Sustainable Outcomes:** Properly interpreting CLD insights fosters sustainable decisions, enhancing overall system performance and long-term viability.

Advantages of System Dynamics Modeling

- **Complex Interaction Understanding:** Modeling enhances comprehension of complex interactions, helping stakeholders visualize and analyze system behaviors effectively.
- **Enhanced Decision-Making:** System dynamics modeling equips decision-makers with insights, improving strategic planning and responsiveness to changing conditions.
- **Adaptive Management Strategies:** Through simulations, organizations can test scenarios and refine management strategies based on anticipated system responses.

Causal Loop Diagrams (CLD)

Causal Loop Diagrams Defined: Causal Loop Diagrams visualize feedback loops and causal relationships, providing a system overview for analysis.

Components of CLDs: Key components include variables, arrows indicating influence, and feedback loops showing interdependencies among elements.

Limitations of CLDs: Despite their utility, CLDs struggle to differentiate between types of flows and complex causal interrelationships.

Numerical Simulation Process 1/3

Modeling and Simulation Process:

- **Formulating the Problem and Defining Modeling Objectives**
  - Identification of the research problem.
  - Determination of the analysis goals.
- **Developing the Conceptual Model**
  - Defining the main factors characterizing the scope of the research task.
  - Establishing causal relationships.
  - Setting the boundaries of the system.
  - Creating a causal-loop diagram (main relationships and feedback loops).
- **Developing the Formal Model**
  - Creating a structural diagram containing the formal description of relationships.
  - Developing the first version of the formal model.
  - Conducting numerical simulation of the first version of the model.
  - Verifying and validating the model by comparing simulation results with real system outcomes.

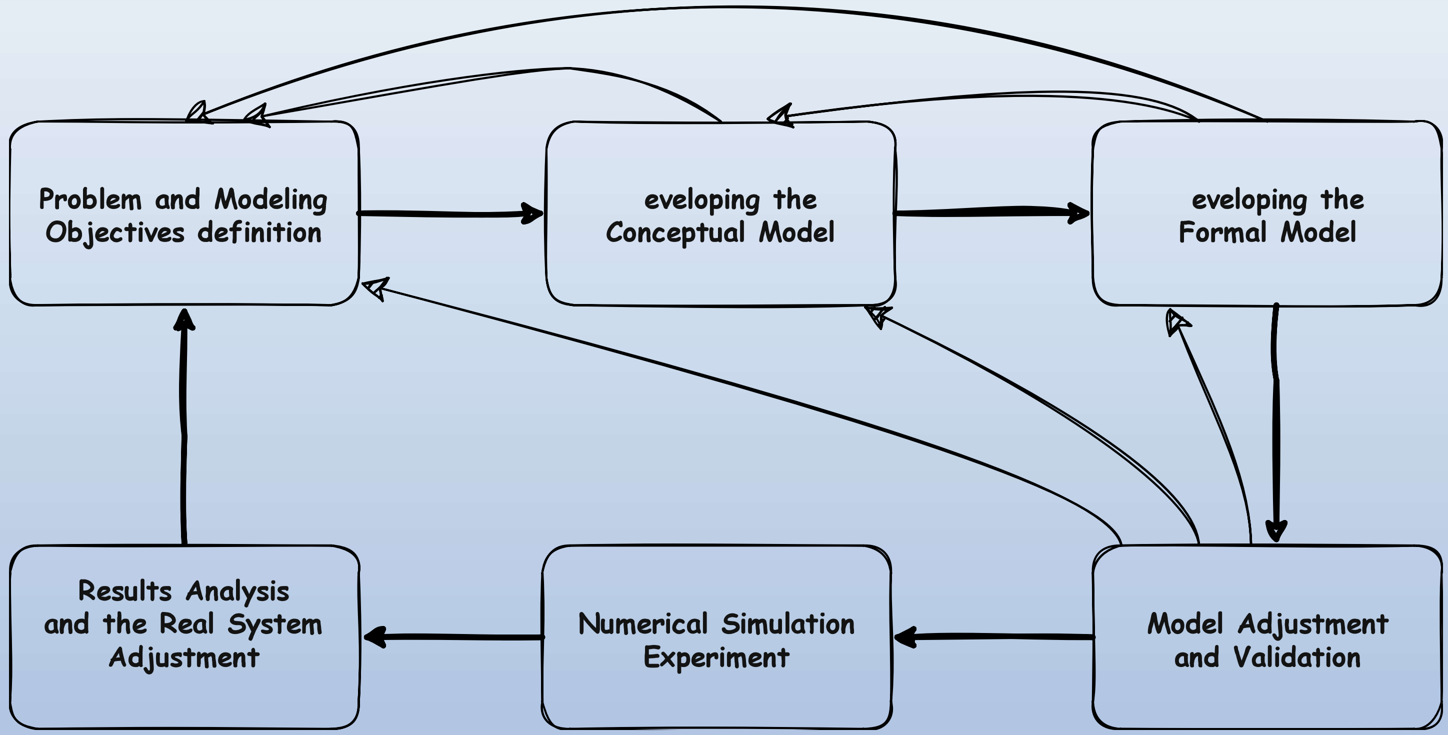
Numerical Simulation Process 2/3

Modeling and Simulation Process :

- **Model Adjustment**
  - Refining the model structure and the characteristics of its elements to achieve the required accuracy level.
- **Numerical Simulation Experiment**
  - Modifying decision variable values in the model to analyze their impact on the system.
  - Conducting a comparative analysis of simulation results before and after modifying decision variables.
- **Results Analysis and the Real System Adjustment**
  - Applying changes established based on the analysis of simulation experiment results.

Numerical Simulation Process 3/3

Modeling and Simulation Process :



Additional Notes:

The modeling process is iterative and often requires revisiting and revising earlier steps.

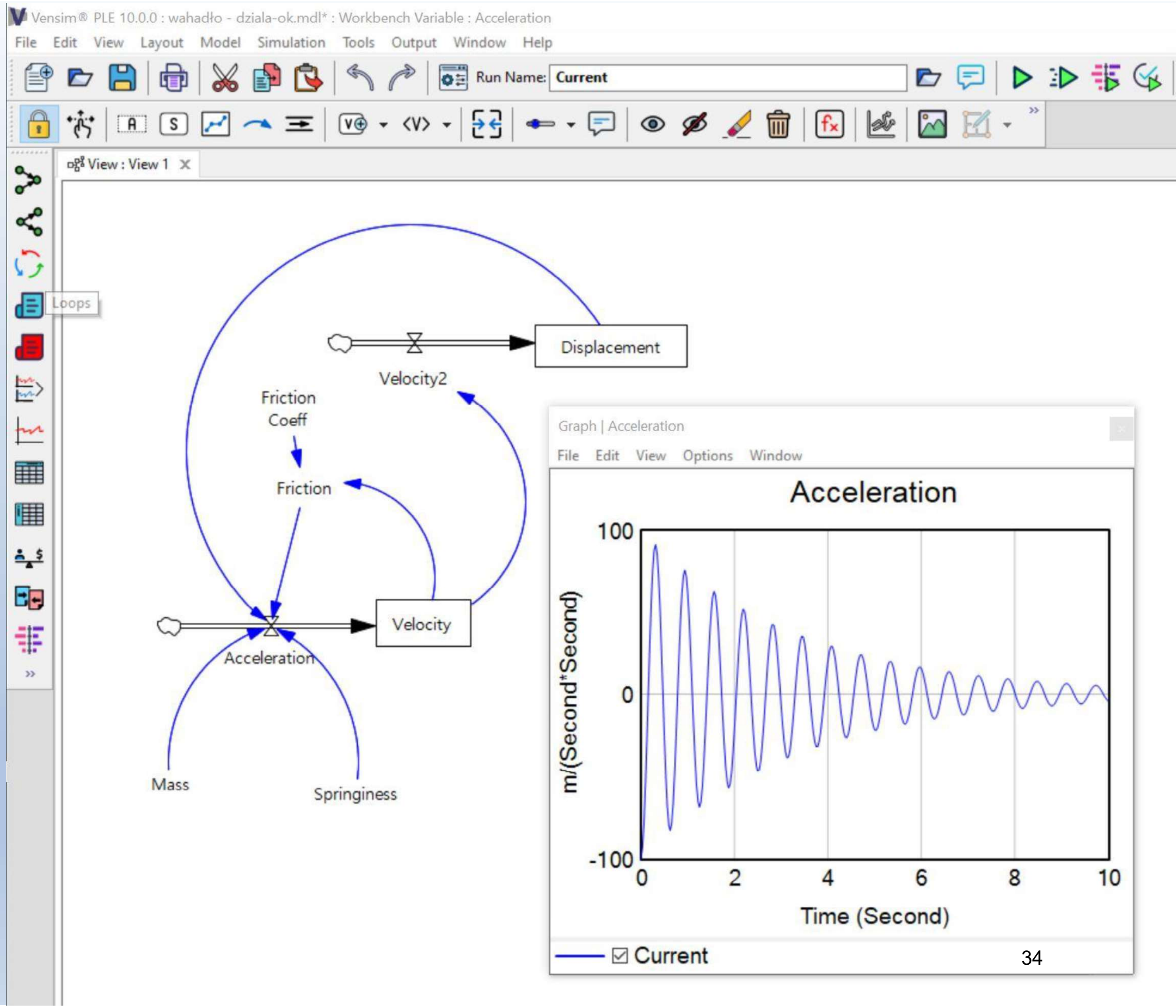
Software Tools for System Dynamics

- **Key Software Tools:** Various software tools support system dynamics modeling, each with unique features and applications.
- **DYNAMO Advantages:** DYNAMO offers robust numerical simulation capabilities tailored for complex dynamic systems analysis and modeling.
- **Vensim Educational Version:** Vensim provides a free educational version, enabling users to model and run simulations effectively.

Vensim Software

- **Vensim Features Overview:** Vensim offers powerful tools for modeling, visualizing, and analyzing dynamic systems effectively in various applications.
- **Personal Learning Edition:** The free Personal Learning Edition allows users to explore system dynamics without financial barriers, promoting accessibility.
- **Advantages of Vensim:** Vensim facilitates intuitive interface design, efficient simulation capabilities, fostering user engagement and rapid model development.

Vensim Software



Accumulation Dynamics

- **Accumulation Concept:** Accumulation in system dynamics represents the change over time, showcasing how inputs affect system states.
- **Equations of Accumulation:** Key equations involve integral calculus, illustrating cumulative impacts through differential equations and flows.
- **Relevance in Systems:** Accumulation is crucial in both natural and technical systems, explaining trends like resource depletion or growth.

Challenges in System Dynamics

- **Challenges in Model Validation:** Validating system dynamics models involves comparing simulations against real-world data to ensure accuracy and reliability.
- **Effective Communication Strategies:** Communicating complex model insights requires tailored approaches for diverse stakeholders to enhance understanding and influence decisions.
- **Limitations of System Dynamics:** Model limitations arise from oversimplification, potential neglect of external factors, and the challenge of accurately capturing dynamic interdependencies.

Real-World Case Studies

- **Industrial Production Case Study:** Examining system dynamics in production efficiency reveals significant outcomes in manufacturing process optimization.
- **Financial Analysis Applications:** Utilizing system dynamics in finance aids in forecasting, risk assessment, and investment decision-making improvements.
- **Real-World Impact Examples:** Highlighted case studies demonstrate tangible benefits from employing system dynamics in diverse industrial sectors.

Conclusion and Future Exploration

- **Holistic Approach Explained:** System dynamics fosters a comprehensive understanding of systems by examining interrelationships among their components.
- **Encouraging Deeper Exploration:** Exploring system dynamics empowers individuals to tackle complex issues through enhanced analytical and modeling capabilities.
- **Broad Applicability:** This methodology transcends disciplines, aiding in decision-making across diverse fields like management, engineering, and policy.

Bibliography

- Litwin P., *Zastosowanie metody dynamiki systemów w analizie procesów produkcyjnych (Application of the system dynamics method to the analysis of manufacturing processe)*, OW PRz, 2023 Rzeszów
- Sterman J. D., Business Dynamics: Systems Thinking and Modeling for a Complex World, *Irwin/McGraw-Hill*, Boston, **2000**
- Angerhofer B.J., Angelis M.C.: System dynamics modelling in supply chain management: research view, ed. by Joines et al. In: *Proceedings of the 2000 Winter Simulation Conference*, **2000**
- Forrester J.W.: Industrial Dynamics: A Major Breakthrough for Decision Makers, *Harvard Business Review* **1958**, 36
- Meadows D. H.: Myślenie systemowe. Wprowadzenie, *Helion*, **2000**
- Forrester, J. W.: Some basic concepts in system dynamics, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, **2009**