On Methodological Research Challenges for Sociotechnical Digital Twin Design for Public Policy

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We bring context, collaborations and cross-domain expertise to invent for real world impact.

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Contents

- Introduction to Digital Twin: Key concepts, definitions and applications
- Digital Twins for a Sociotechnical ecosystems: Additional requirements and methodological challenges
- Case studies from public policy
- Open challenges with using Sociotechnical DTs
- Concluding remarks

A leading UK research centre in Digital Twin – activities in:

DT Foundations

- 5g/6g Communications
- Architectural description lanaguages for federated twins
- Information Frameworks

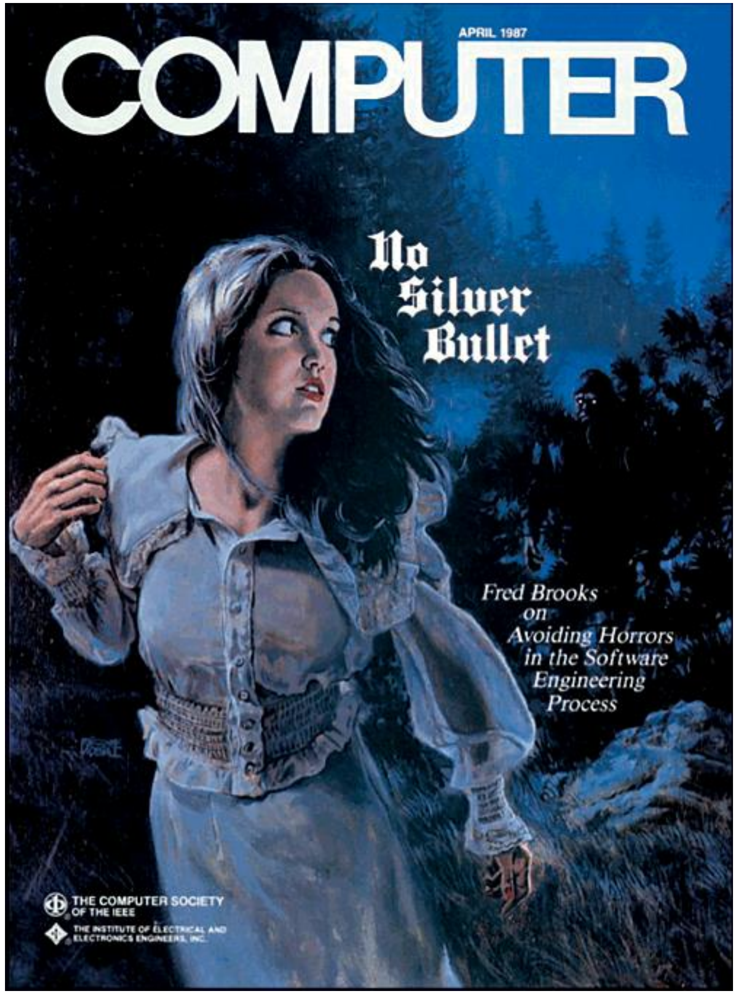
DT Enabling Technologies

- Methods and Software Tools for DT Design
- ML workflow and integration
- Visualisation and Simulation Languages and Tool integration

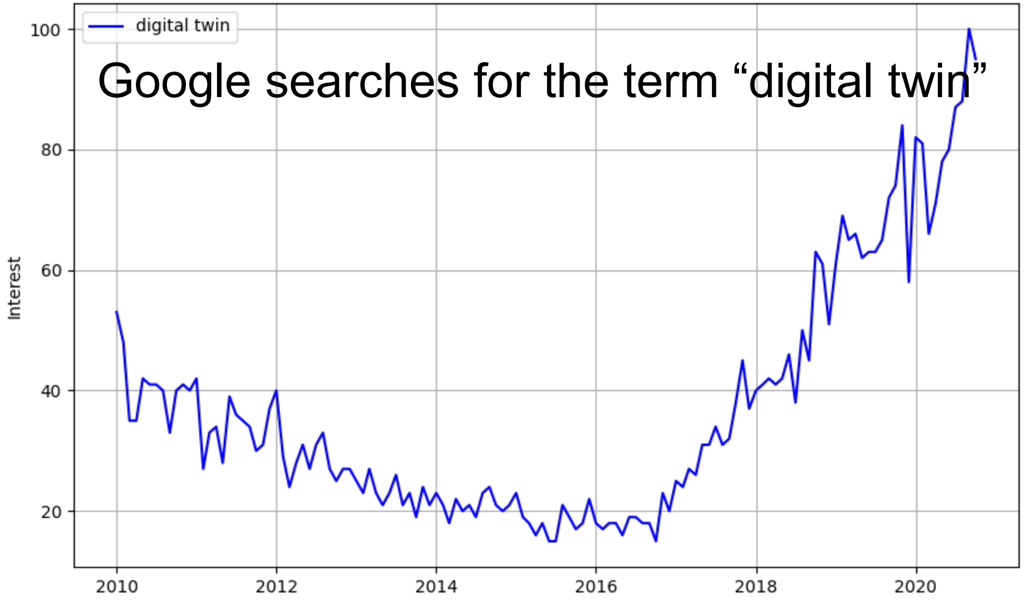
DT Applications

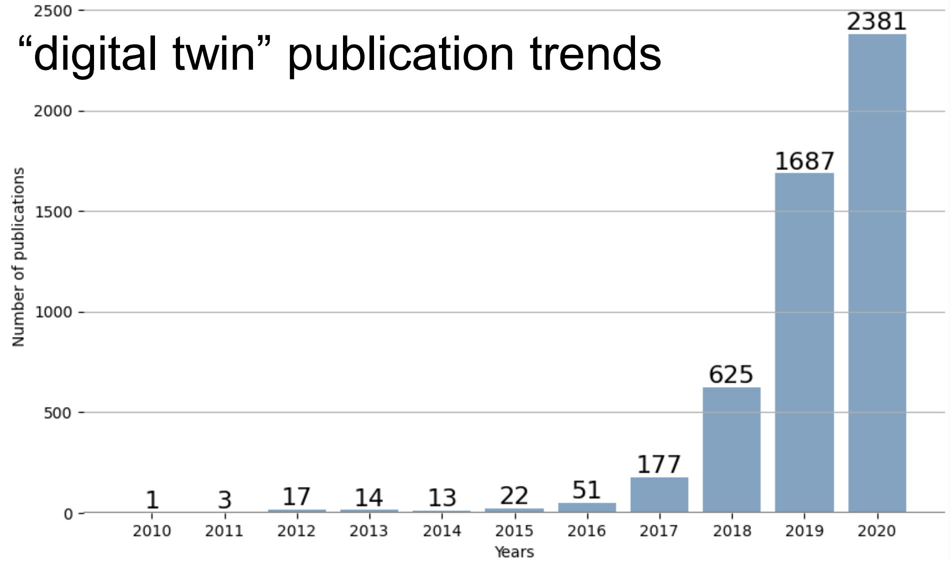
- Stroke Care
- Agriculture
- Heritage Artifacts
- Enterprise
- Public Policy
- Health care resilience
- Infrastructure Health

Digital Twins: The new silver bullet?



1987: “there is no single development, in either technology or management technique, which by itself promises even one order of magnitude [tenfold] improvement within a decade in productivity, in reliability, in simplicity."



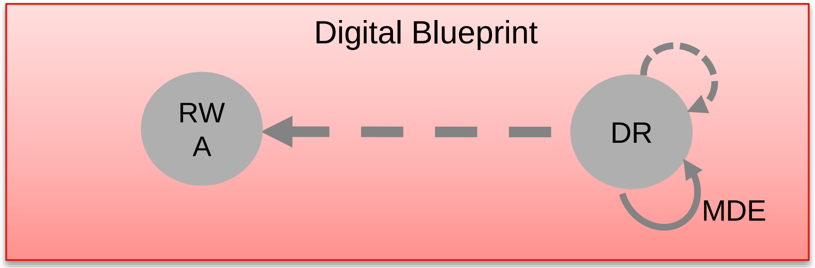


Definitions and characteristics based on meta review on Digital Twin Research

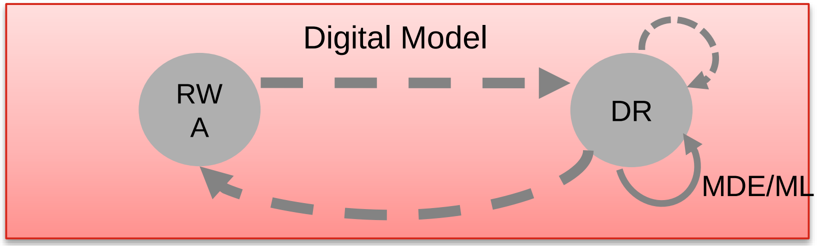
- Constructs and Fidelity
  — Modelling constructs to define construct high fidelity virtual representations of real physical resources.
- Seamless connection
  — Dominant aspect that characterizes different types of Digital Twin. Connection determines synchronization between real world artifact and the digital representation
- Safe Simulation Environment
  — Testing impact of change intentions (cheaply /risk-free)
- AI/ML in Digital Twin
  — Learning mechanisms to support self-adaption, self regulation, self-monitoring and self-diagnosis

A pure-play Digital Twin is a **self-adapting**, self-regulating, self-monitoring, and self-diagnosing system-of-systems which is characterized by a symbiotic relationship between a physical asset and its virtual representation, whose fidelity, rate of synchronization, and choice of enabling technologies are tailored to its envisioned use cases, and which supports services that add operational and business value to the physical asset.

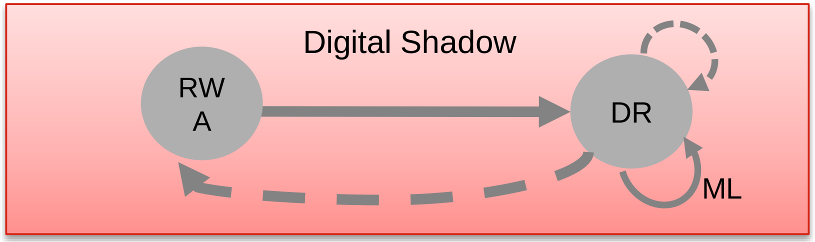
Seamless communication contributes to defining Different Types of Digital Twin



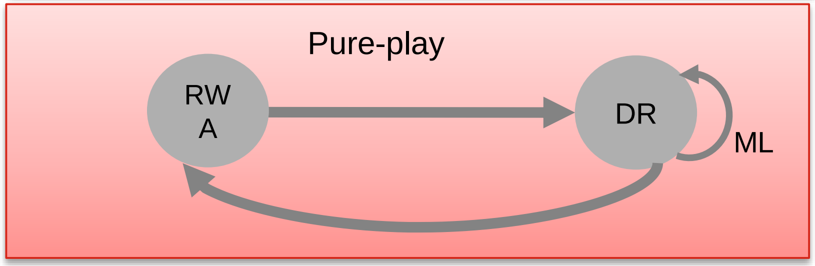
A “traditional” computational model. Mostly manual synchronization processes, some use of MDE. We could envisage this a bespoke software tool to represent a Real World Artifact. The digital representation is used as a blueprint for RWA.



A “traditional” computational model. Mostly manual synchronization processes, some use of MDE. Aspects of the RWA are manually entered to develop the DR. Some use of MDE practice and also ML to inform the development of DR, self-regulation and self-adaptation. The RWA is updated manually.



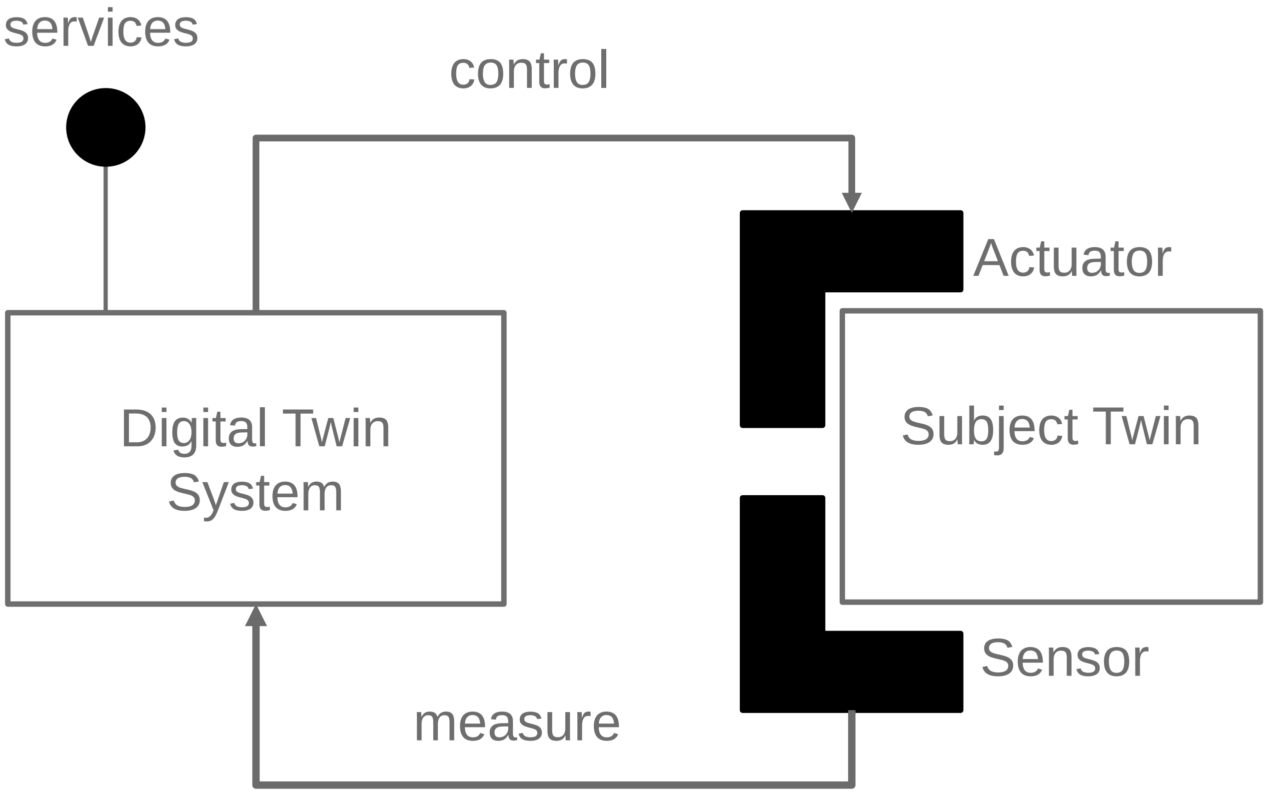
Recognisably a DT as popularized. Periodic but regular automated synchronization to the DR. Use of both manual methods and ML to inform the development of DR, self-regulation and self-adaptation, self diagnosis and other aspects. The RWA is updated manually.



Pure example of DT. Self-evolving through the use of AI/ML. Automated synchronization between the RWA and DR..

RWA: Real World Artifact
DR: Digital Representation

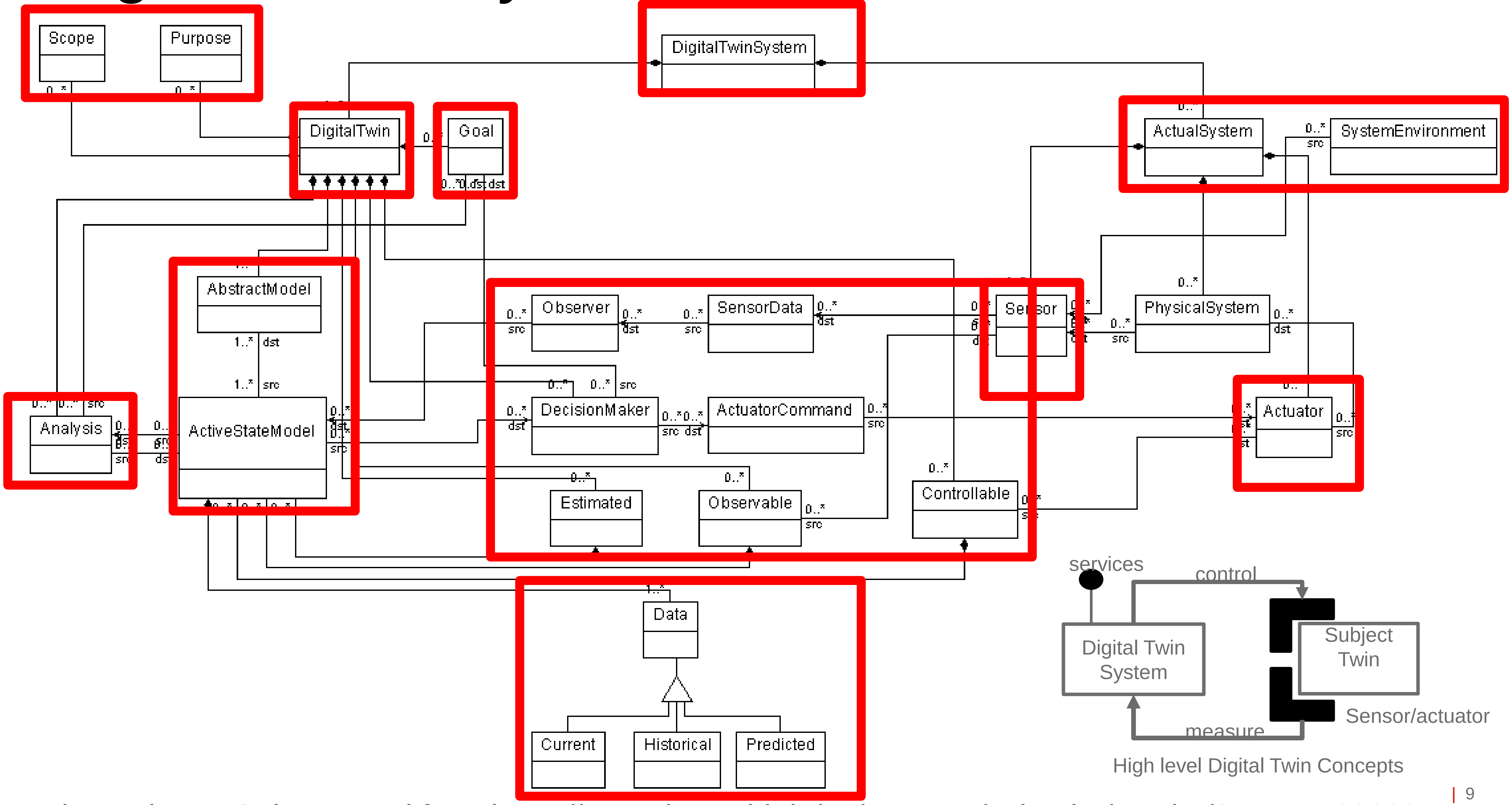
Conceptual Architecture of Digital Twins



High level Digital Twin Concepts

- Applicable:
- NASA use of controllers
- Infrastructure monitoring
- Smart City planning
- Sociotechnical ecosystems such as for exploring pandemic control or Levelling up

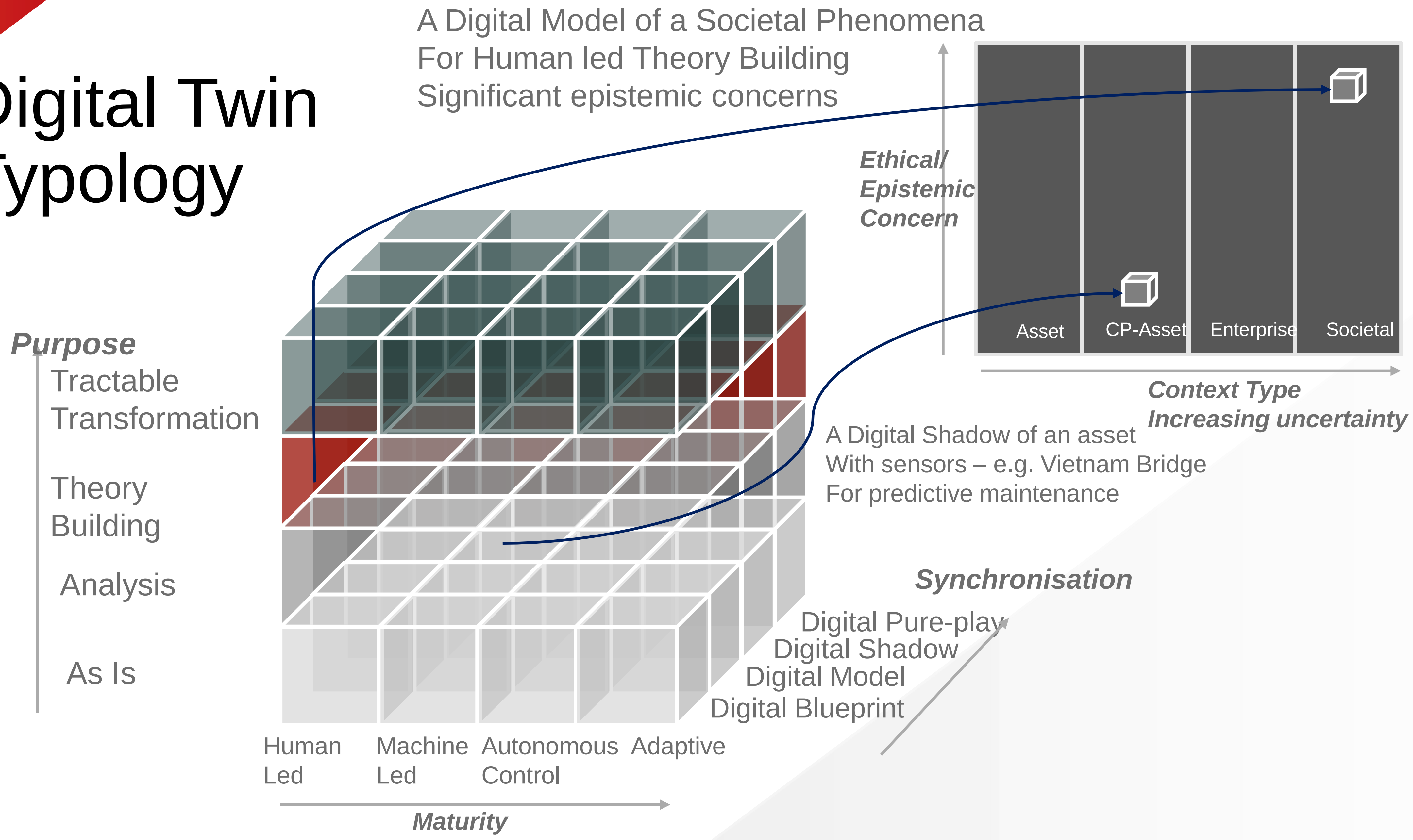
Digital Twin Key Concepts



High level Digital Twin Concepts

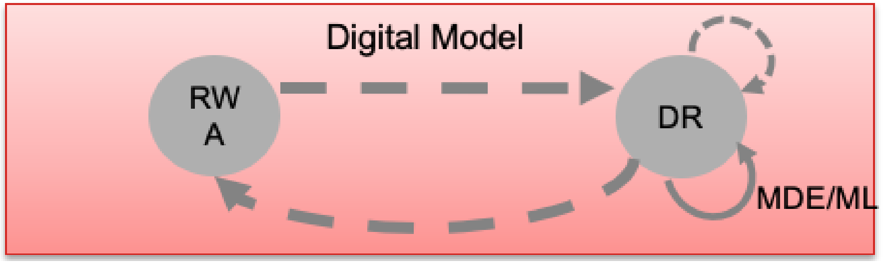
Figure due to Gabor Karsai from https://www.dagstuhl.de/en/program/calendar/semhp/?semnr=22362

Digital Twin Typology



Digital Twin – Sociotechnical Digital Twin

- Digital Twins (Computational Models) of phenomena that model elements of human interaction are sociotechnical systems (Mumford)
- Sociotechnical Digital Twins are:
  - Complex
  - Dynamic
  - Engage multiple disciplines (leading to language concerns)
  - Demand simulation as an underpinning methodology for data generation
  - Ideally suited to Agent based models rather than physics based models



- Other characteristics of Agent based systems include:
  - Autonomy: agents are autonomous information processing and exchanging units, free to interact with other agents
  - Heterogeneity: types of agents
  - Active: agents are goal-directed, reactive, (bounded) rationality, interactive, mobile, adaptive, learning
  - Interdependence: agents influence others in response to the influence that they receive directly or through the env.

A “traditional” computational model. Mostly manual synchronization processes, some use of MDE. Aspects of the RWA are manually entered to develop the DR. Some use of MDE practice and also ML to inform the development of DR, self-regulation and self-adaptation. The RWA is updated manually.

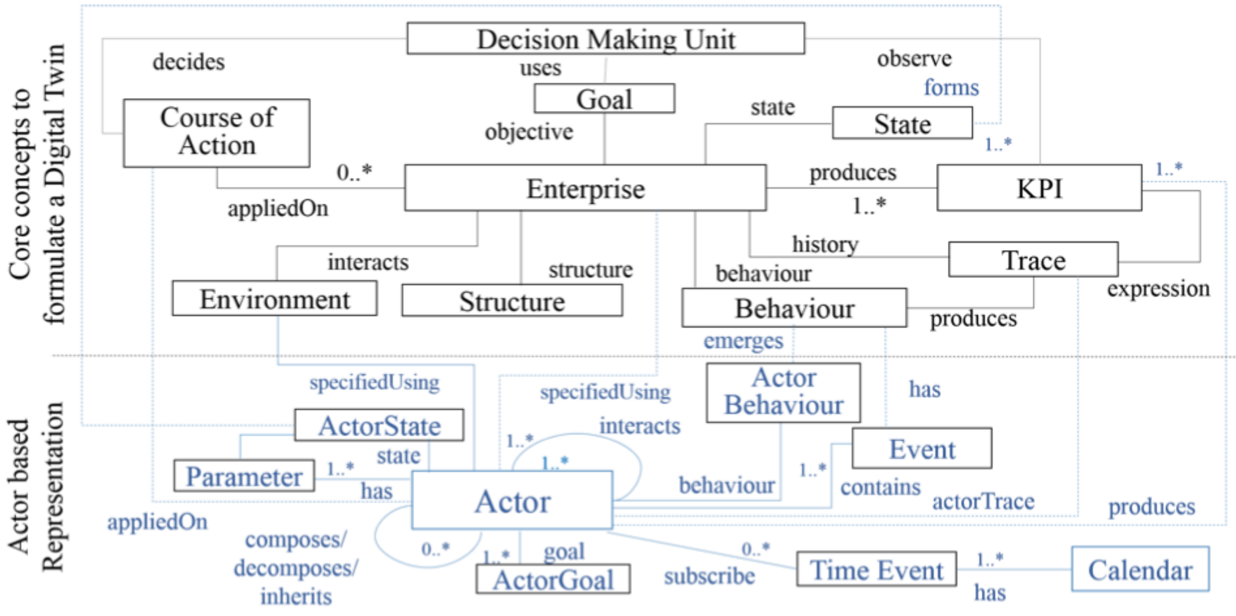
Sociotechnical Digital Twin: A Definition

A Sociotechnical Digital Twin is a system-of-systems that can include a learning component which is characterized by a relationship between a real world system and its *partial* virtual representation, whose fidelity, rate of manual synchronization, and choice of enabling technologies are tailored to theory exploration and explanation and will include a mix of modeling approaches including agent based simulation.

B. S. Barn: The Sociotechnical Digital Twin: On the Gap Between Social and Technical Feasibility. CBI (1) 2022: 11-20

TCS-MDX-ASTON Research on Sociotechnical Digital Twins

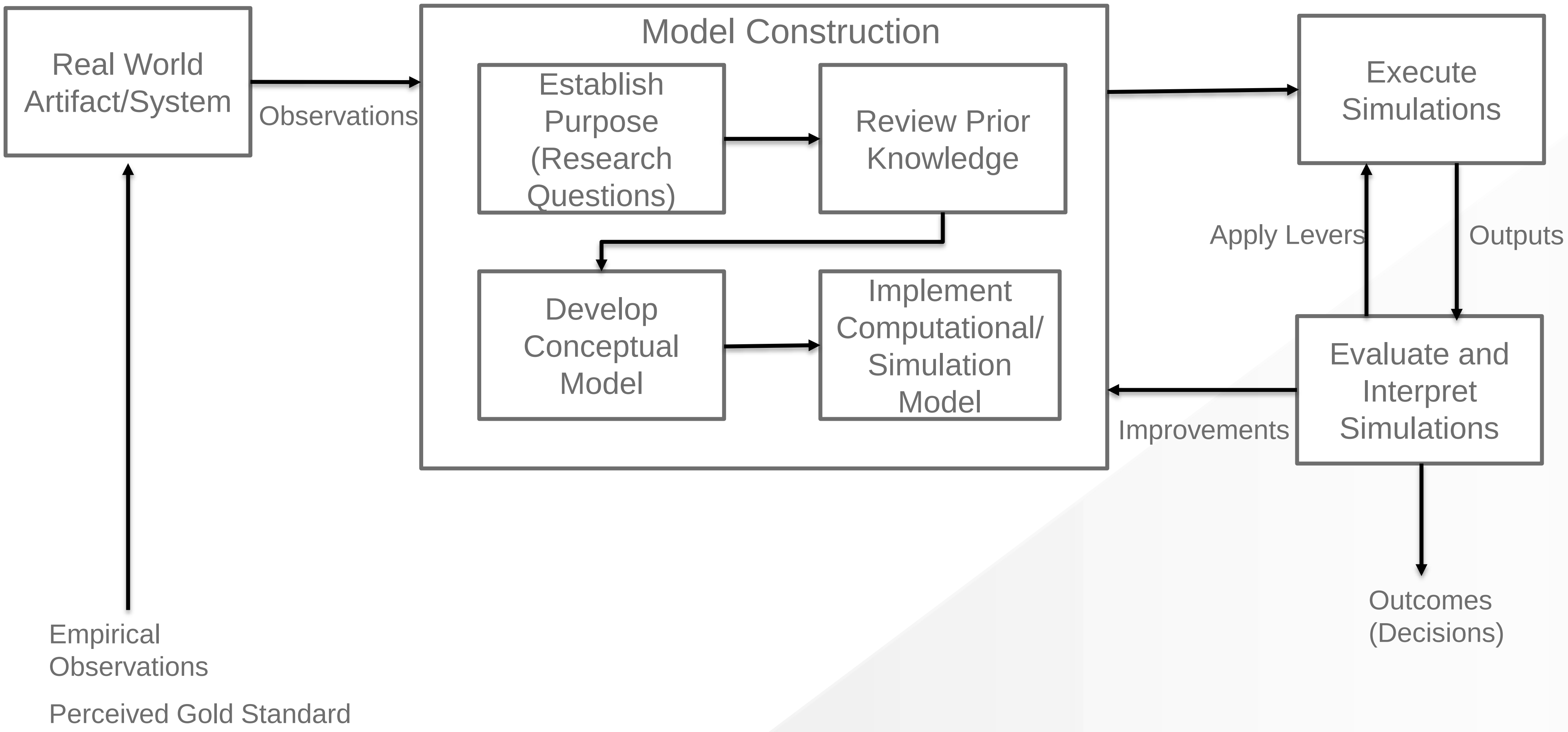
- Organisational Decision Making
  - Modelling the complexity of organizational structures and human behaviour to support decision making
- De-monetization – India 2016
  - Representing the behaviour of Indian society as a result of the removal of bank note denominations.
- Covid-19 Pandemic Modelling of the City of Pune, India



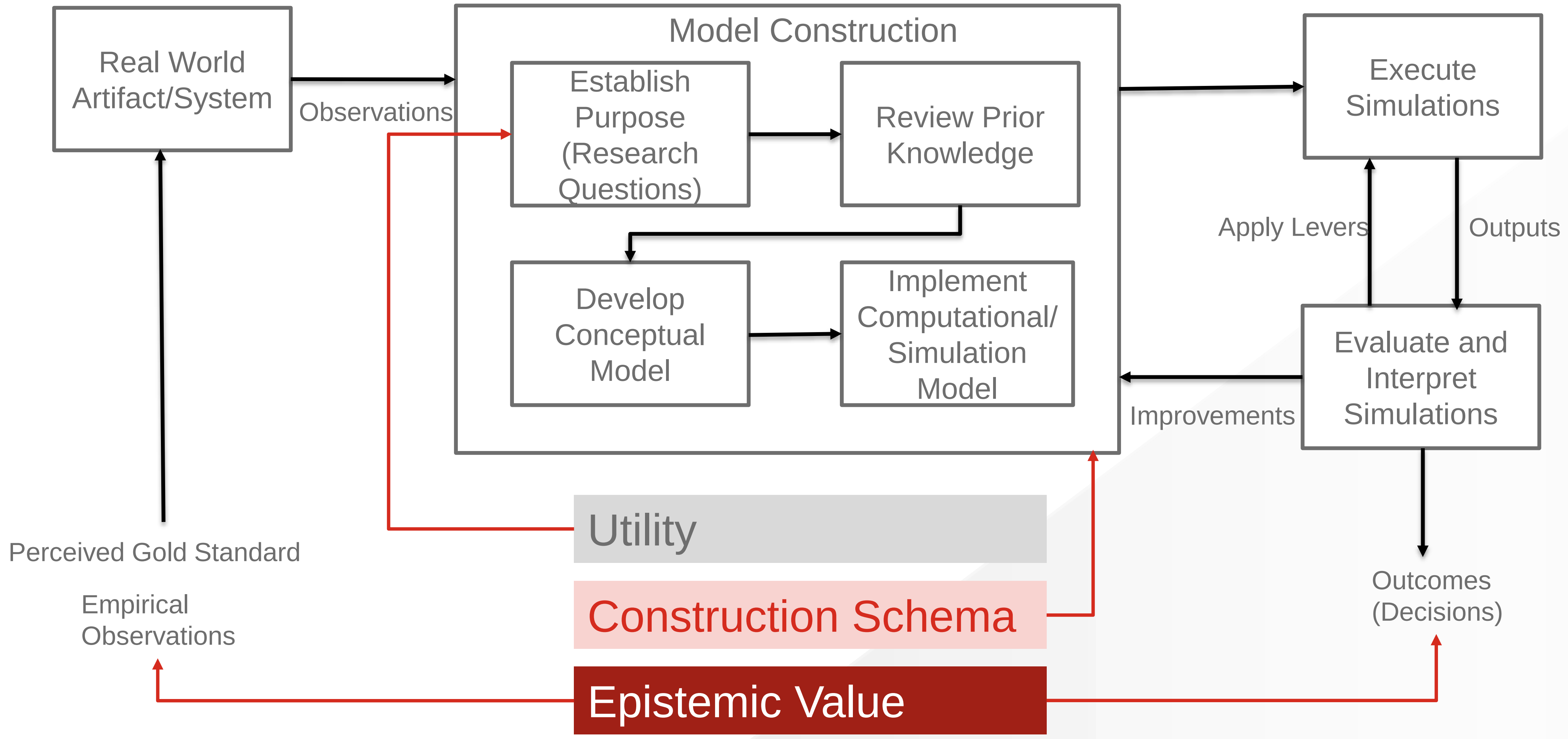
Actors:
Actor Model of Computation
Concurrent objects, emergent behaviour, system models.
Agents:
Independent goal directed behaviour, system models.
Machine Learning:
Adaptation based on historical execution, Reinforcement Learning.

esl-lang.org

Canonical DT Design and Implementation



Canonical DT Spec, Design and Implementation



Construction Schema

Techniques for specifying and implementing a real world artifact as an abstraction and computation oriented element include recursive construction schemas:

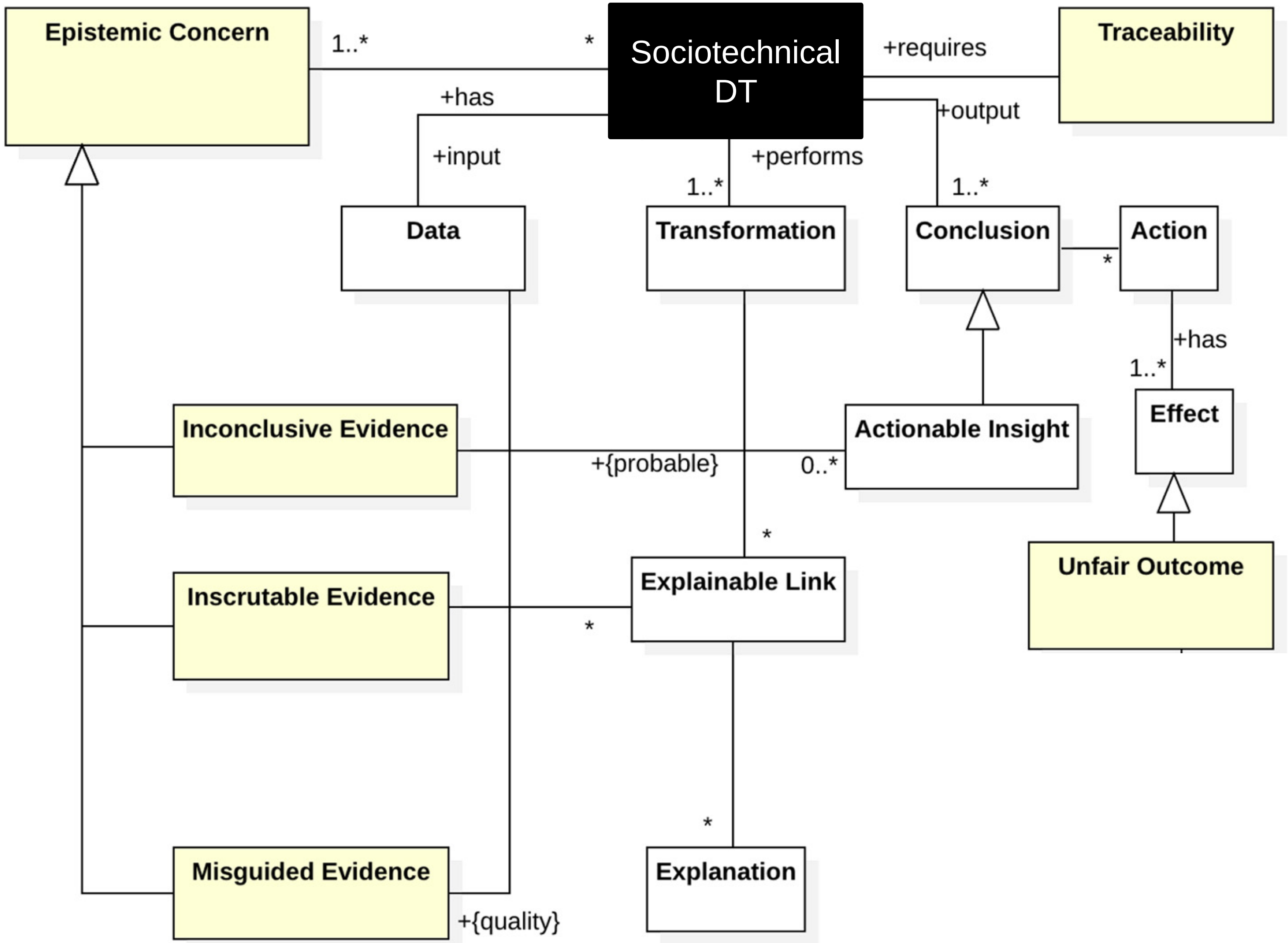
- Physics based reduction
  - using the laws of physics of denote behaviour (finite element analysis in digital bridge representations
- Component based reduction:
  - Decomposition through component-based design to go to smaller, well-defined behaviours .
- Abstractions
  - manage scope and complexity (an agent based representation of movement of human actors in an airport don’t show details of the functioning of the liver);
- Theories from social science to denote human behaviour (some specific challenges here)

Digital Twin Utility

- Models can have a useful purpose but they can never be perfect (reduction/simplification through construction schema).
- Useful purpose: We build ST DTs to gain, extend, or clarify knowledge.
- ST DT Purpose
  - As Is Analysis (Model validation: Model Results are the same as RW Observations)
  - Theory Building – Assumptions, Hypotheses tested lead to new propositions (Model validation: cyclical, with accepted levels of confidence (co-validation with stakeholders)
  - Exploitation: A means by which the outcomes can be used in decision making

Epistemic Value (Trust)– from Mittelstadt et al.

- Inconclusive evidence:
  — Inferential, probable, epistemic limitation
- Inscrutable evidence
  — Connection between data and conclusion should be accessible.
- Misguided evidence
  — Conclusions and actions only as reliable as the data
- Unfair outcomes
  — Outcome should be fair even if action is scrutable, and well founded.



Balbir S. Barn, Mapping the public debate on ethical concerns: algorithms in mainstream media. J. Inf. Commun. Ethics Soc. 18(1): 124-139 (2020)

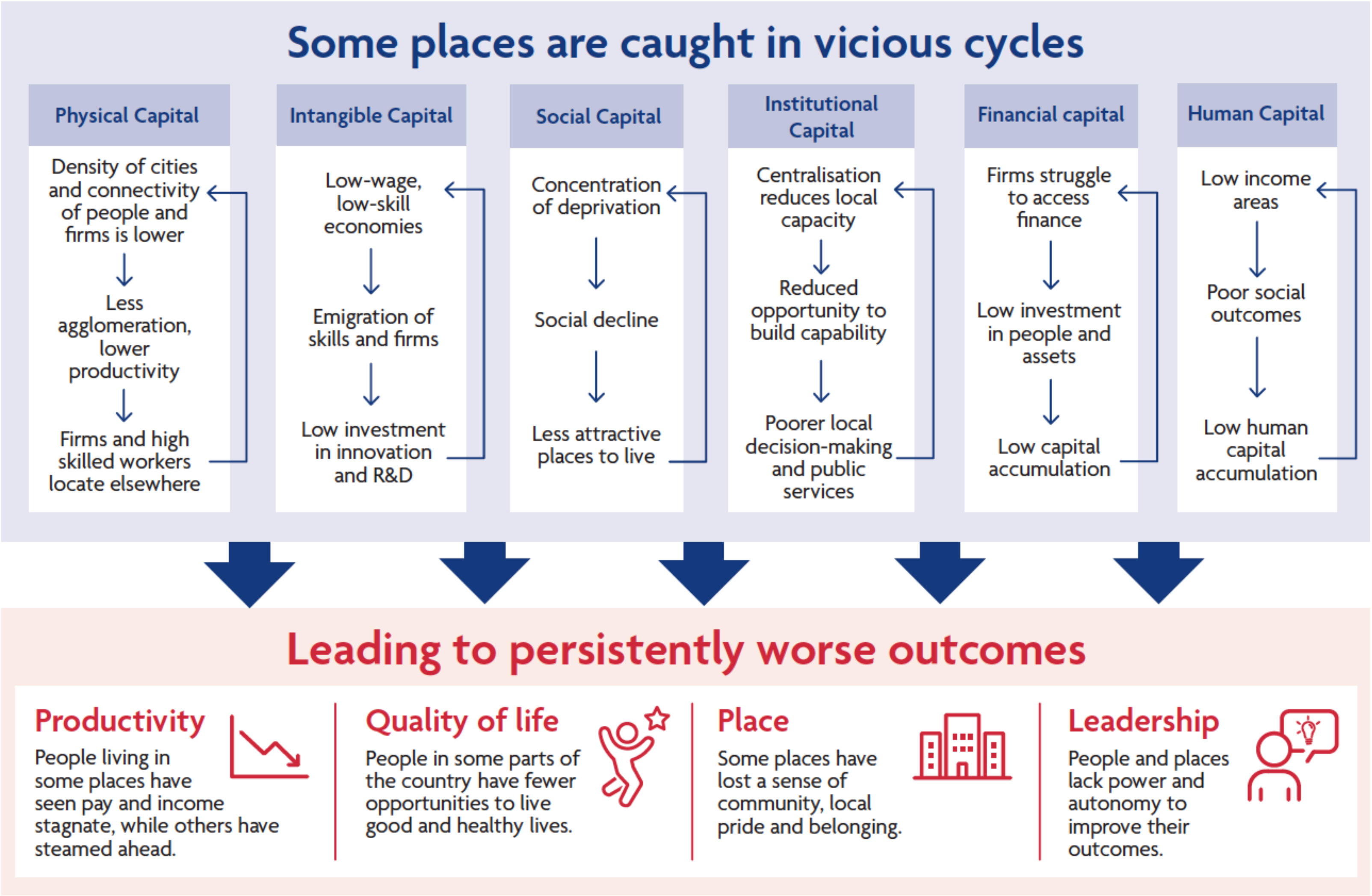
Problems in Public Policy: LEVELLING UP

- Disparities in growth in different regions based upon:
  - physical, human, intangible, financial, institutional and social “capitals”
  - Agglomeration and clustering effects are cumulative in successful places, as they serve as a magnet for people, business, finance and culture, locking them into a high growth equilibrium
  - The reverse forces operate in struggling places, repelling people, business, finance and culture and locking places into a low-growth equilibrium.
- Movement of people between regions is the main link between the different capitals.

Underlying theory and assumptions

- Economic growth theories indicate:
  - Productivity increases with increased investment in various capitals

Figure 1.62 Levelling Up Capitals Framework

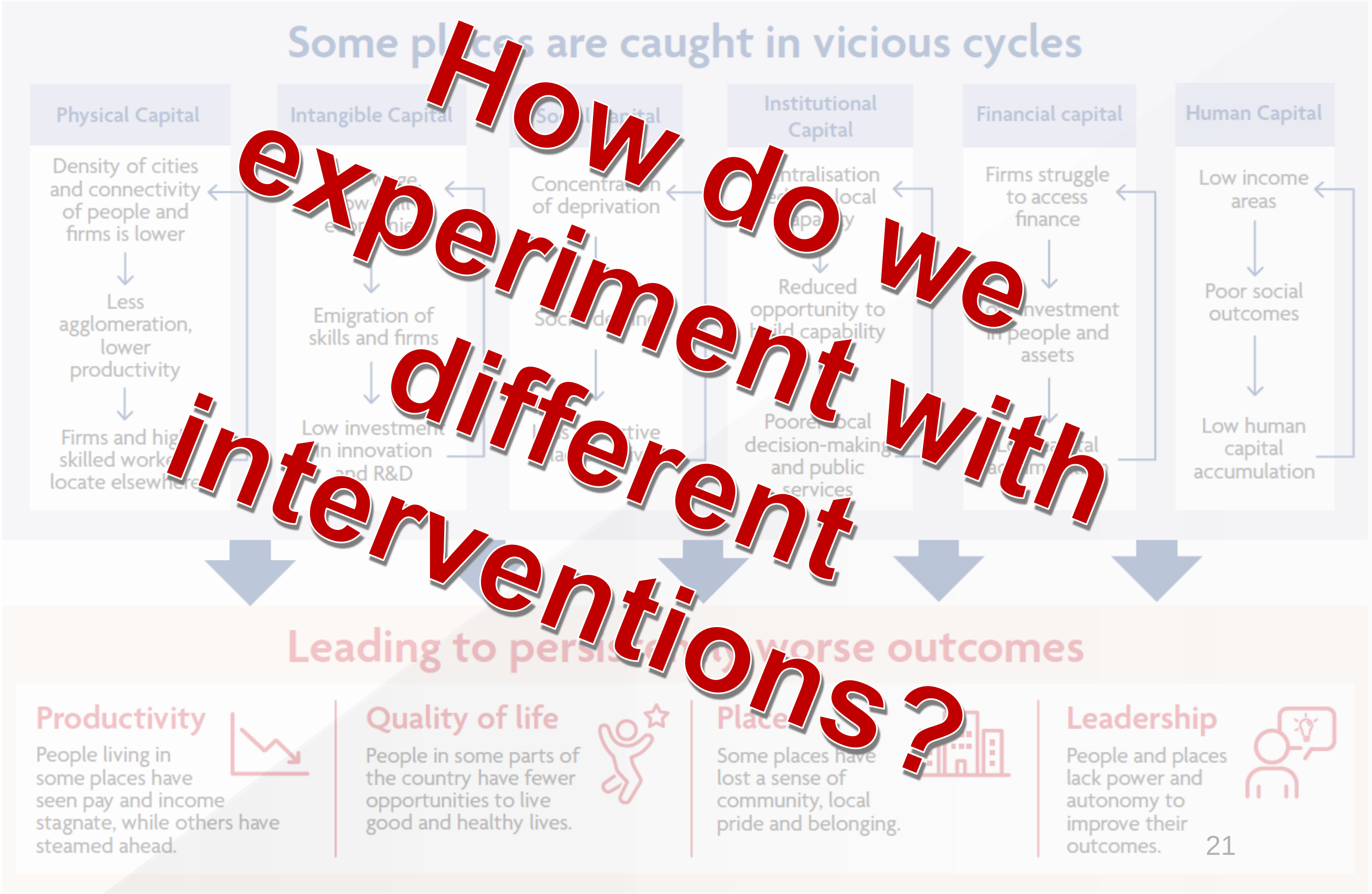


Underlying theory and assumptions

- Economic growth theories indicate:

Productivity increases with increased investment in various capitals

Figure 1.62 Levelling Up Capitals Framework

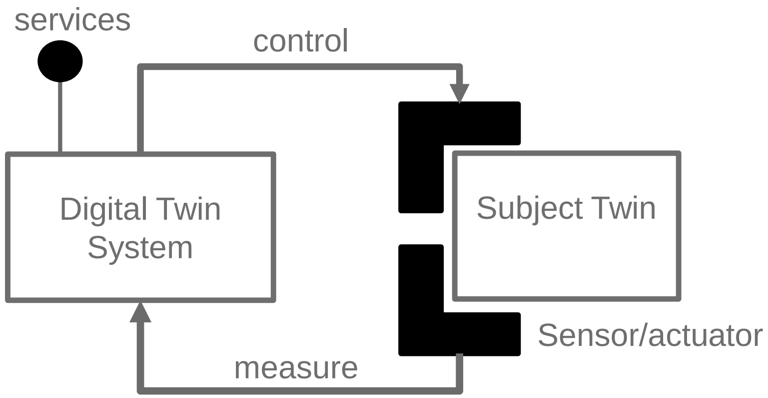


How do we experiment with different interventions?

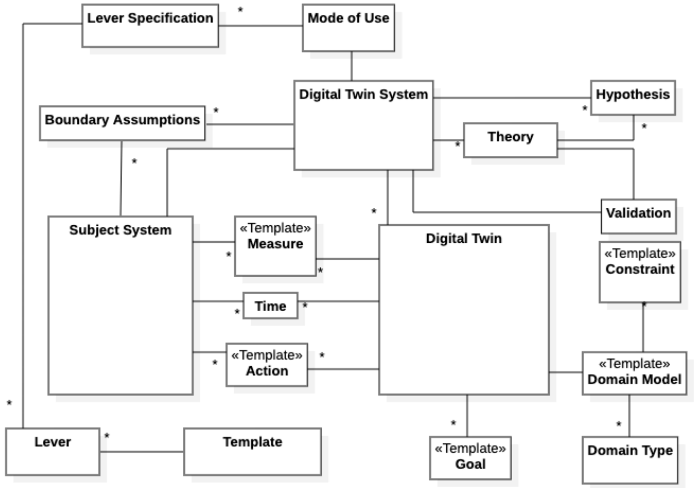
What's needed to build this experiment? SPECIFICATION FIRST

- Concepts with well understood semantics to represent the problem domain.
- A method for translation from the problem domain to the implementation domain that:
  — Captures domain concepts – A "language for specifying ST Digital twins"
  — Encourages collaboration and leads to shared understanding.
  — Recognises that domain experts provide knowledge and should not focus on modelling.

Language concepts



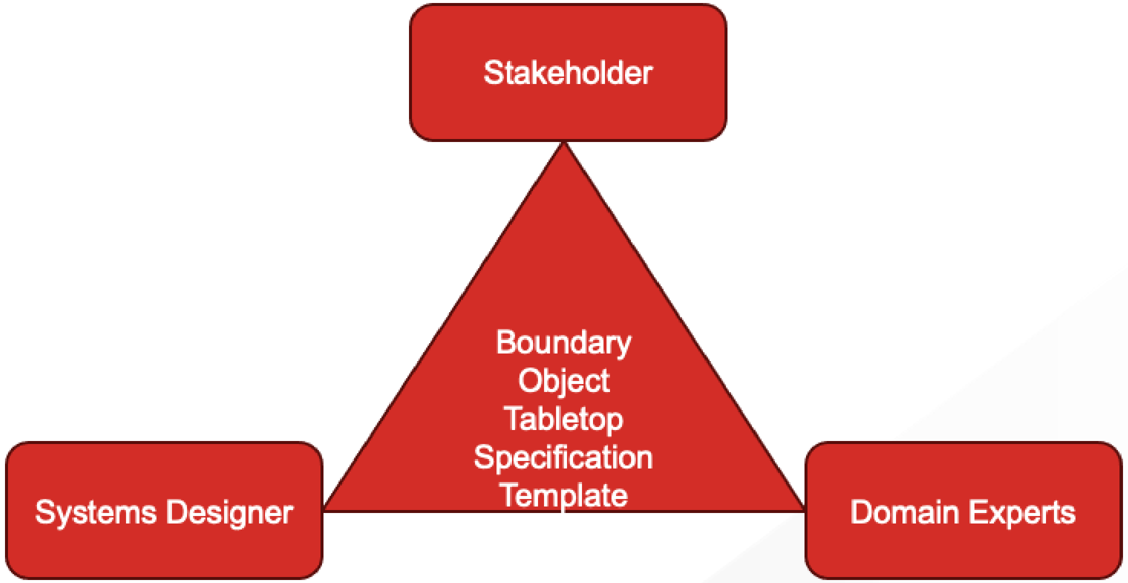
High level Digital Twin Concepts



Concept	Description
Assumption	Used for defining the scope of the subject and target digital twin system
Validation	Underpinning external references to theories for justification of model elements
Constraint	Domain level rule constraining behaviour (invariant)
Goal	Objective / purpose of the DT
Measure	Property of the domain model that is quantifiable in some way
Lever	Property of the domain model of the DT that can be changed through external control
Regulation	Enforceable policy such as a planning rule
Domain Model	Concepts from the problem domain - key business objects
Actions	Behaviour (operation specifications) assigned to domain concepts in the domain model

A light weight paper template

- Translates the formal language into a “boundary object”* that builds a shared understanding of the problem domain with system designers.
- Co-specification with designers and domain experts
  - Agree construction schemas
  - Agree parameters for validation
  - Acknowledge bias possibilities
- Co-Specification with stakeholders
  - Agree utility (purpose)
  - Can acknowledge bias
  - Can establish trust
  - Can determine parameters of efficacy of outcomes



* Star S. L., Griesemer J. R. (1989). Institutional ecology, ‘translations’ and boundary objects: Amateurs and professionals in Berkeley’s Museum of Vertebrate Zoology, 1907–39. *Social Studies of Science*, 19, 387–420.

GOALS

MEASURE

HYPOTHESIS/ASSUMPTION

LEVER/POLICY

REGULATION

CONSTRAINT

DOMAIN CONCEPT MODEL

VALIDATION

ACTIONS

STATE MODEL

GOALS

Boost productivity

Restore Community Belonging

Empower local leadership

Understand the interplay of different Types of capitals

MEASURE

Summary Level Indicator of a region

Capital measures

Amount produced per unit of input

Degree of centralization

HYPOTHESIS/ASSUMPTION

Improving physical capital leads to greater productivity

Access to financial capital leads to greater productivity

LEVER/POLICY

Provide a local growth fund
Infrastructure investment
R & D Scheme
Home building programme
Domestic Regeneration.

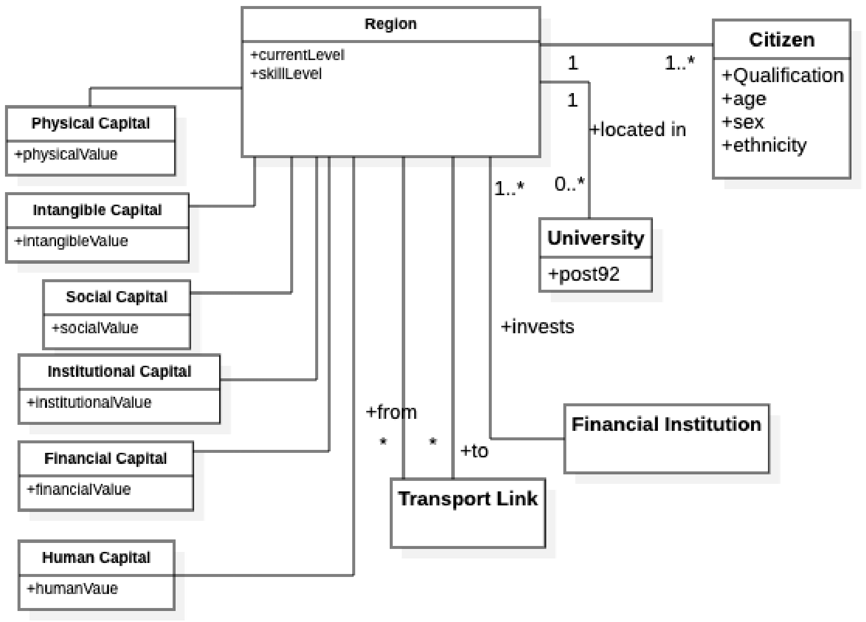
REGULATION

Planning Permission
Conditions on investment
Minimum thresholds on grants

CONSTRAINT

Properties of citizens and regions are within limits

DOMAIN CONCEPT MODEL



VALIDATION

Accepted theories
- Theory of Economic Growth
- Putnam’s Social Capital Theory

Will be run against historical examples of regional growth and decay

ACTIONS

Financial investments are made by Financial Institutions leading to increase in financial capital, intangible capital
Citizens tries to perform behavior (“live”) using regional resources
Region performs next steps in action plan.
Region updates measures
Citizens (young graduates) move to regions where there are jobs and demand fo
Knowledge based skills

STATE MODEL

Citizen. Education {Schooled, Graduated}
Region. Current Level {Overheated, Growing, Declining}
A typical starting state or terminal state

A Sociotechnical digital twin for Serious Organised Crime (SOC) in Prisons

What technological innovations can be deployed to test the efficacy of different policy interventions for reducing serious organized crime in prisons?

- Understanding the current situation;
- Determination of key factors either encouraging or inhibiting activities that impact on SOC.
- Developing multiple perspectives of the situation from different stakeholder perspectives.

Funding limited:

- Utility:
  — Focus on Understanding (As Is and Theory Building)
- Construction schema:
  — Abstractions
  — Theories from social sciences
- Epistemic Value
  — Model validity through co-design and co-review

<Assumption>: <Measure> : <Up | Down | Stable> : <probability>

GOALS

Degrade Efficacy of OCGs in prisons

Reduce prison related crime →

MEASURE

Drug volume in prison

no. of crimes in prison

HYPOTHESIS/ASSUMPTION

prison visits reduction : ↓ drug vol, crimes

body checks of visitors : ↓ drugs

drugs reduction : ↓

LEVER/POLICY

L1: Reduce short term sentences

L2: Visitor checks (BOSS chair)

L3: worker security check

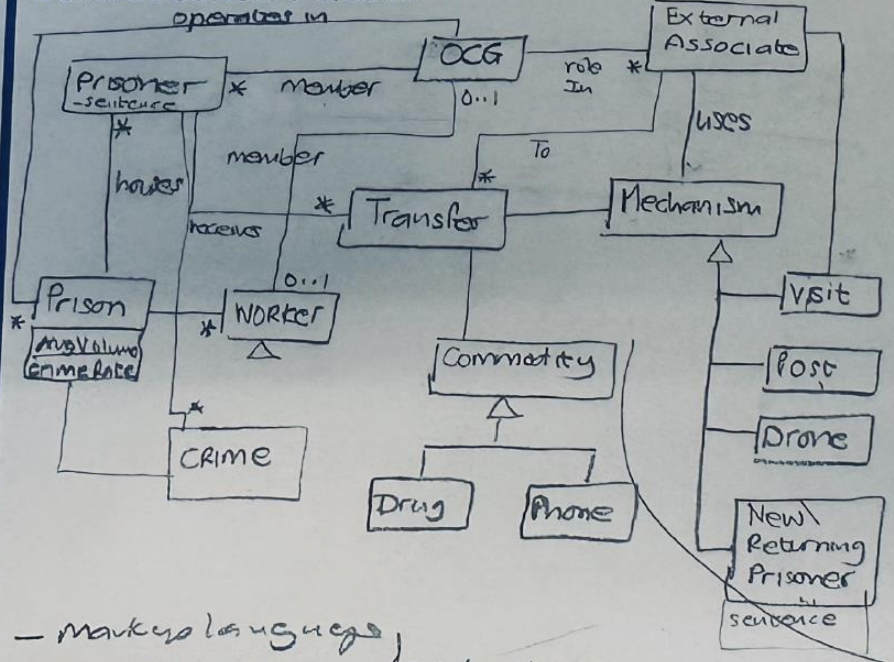
L3: Transfer between prisons

L4: Phone Jamming

REGULATION

CONSTRAINT

DOMAIN CONCEPT MODEL



– markup languages to make ... from smalltalk language

VALIDATION \ Provenance

model.element linked to provenance fact

Fact base

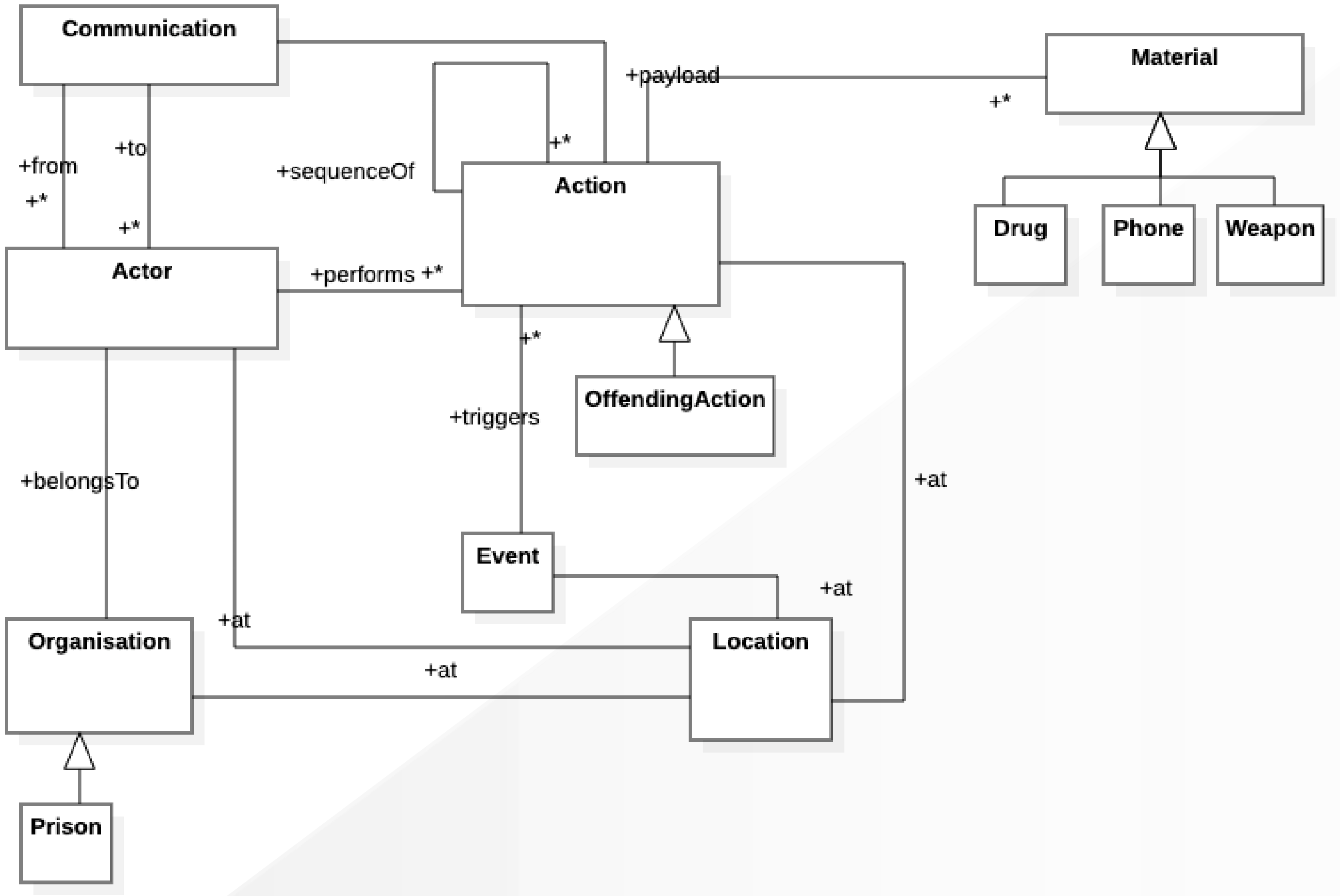
ACTIONS

STATE MODEL

Prisoner.member.ocg {not member, member}

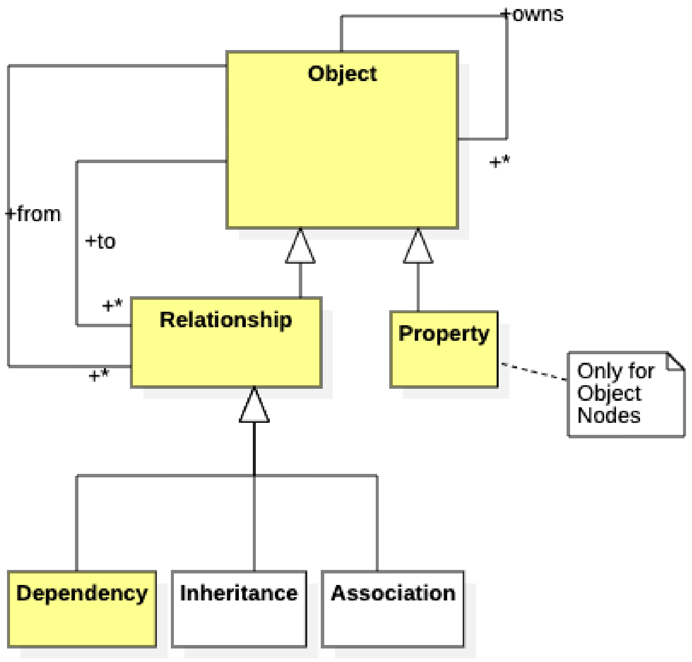
A Sociotechnical digital twin for Serious Organised Crime (SOC) in Prisons (2)

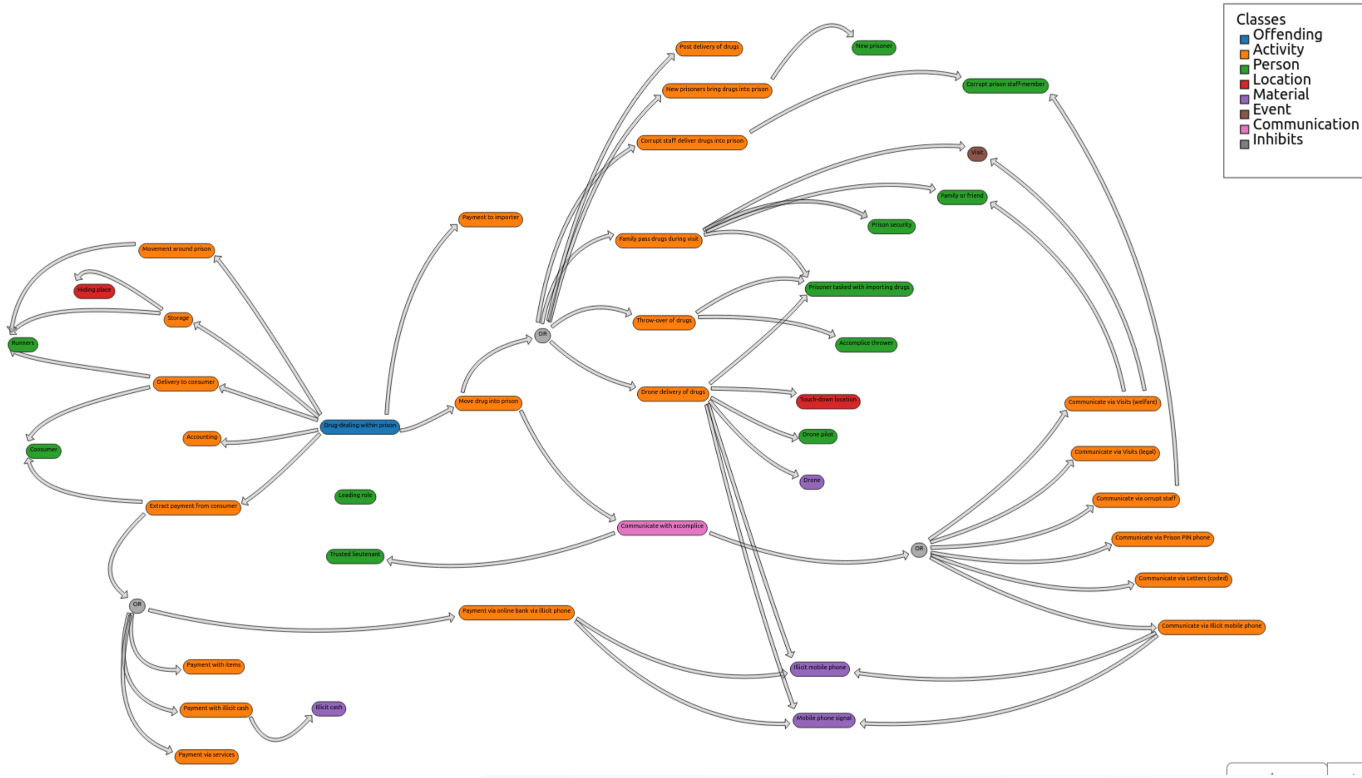
- Use of a target Modelling Tool owned by industrial Partner (Sketch)
  - Platform Specific Modelling Language
  - Used for understanding the problem and capturing workshop content with domain experts
- Design of Domain Specific Modelling Language for SOC



A Sociotechnical digital twin for Serious Organised Crime (SOC) in Prisons (2)

- Project “sold” on the basis of the use of a target Modelling Tool owned by industrial Partner (Sketch)
  - Platform Specific Modelling Language
  - Used for understanding the problem and capturing workshop content with domain experts

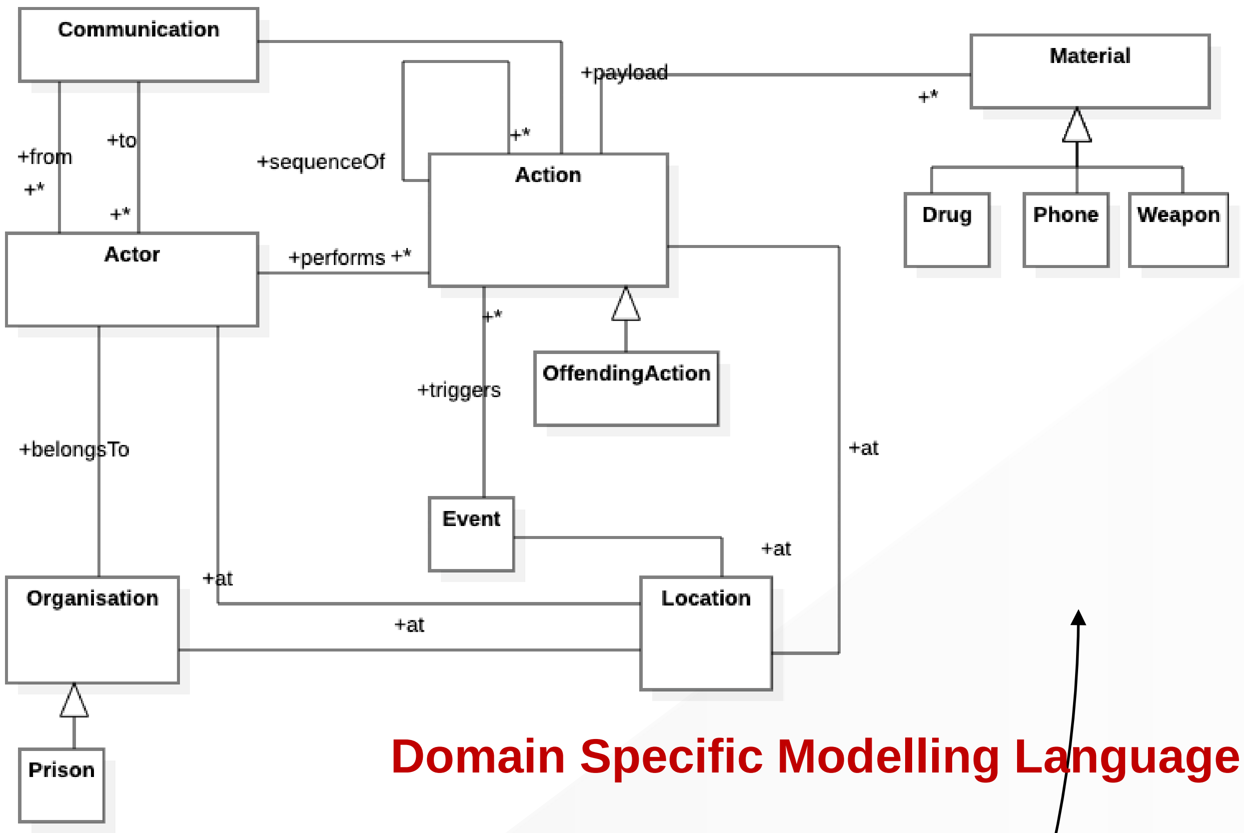




https://beta.sketch.cosimmetry.co.uk/board/649cc912-14fe-4262-9239-09dc822e0eb4/base-layer#

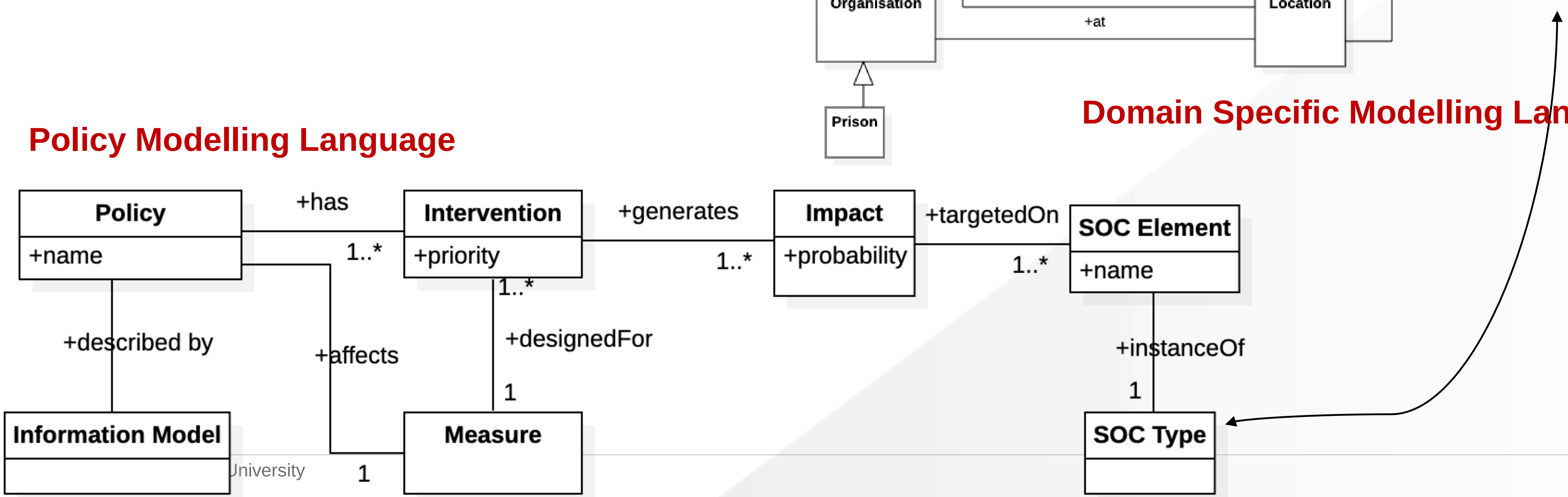
A Sociotechnical digital twin for Serious Organised Crime (SOC) in Prisons (2)

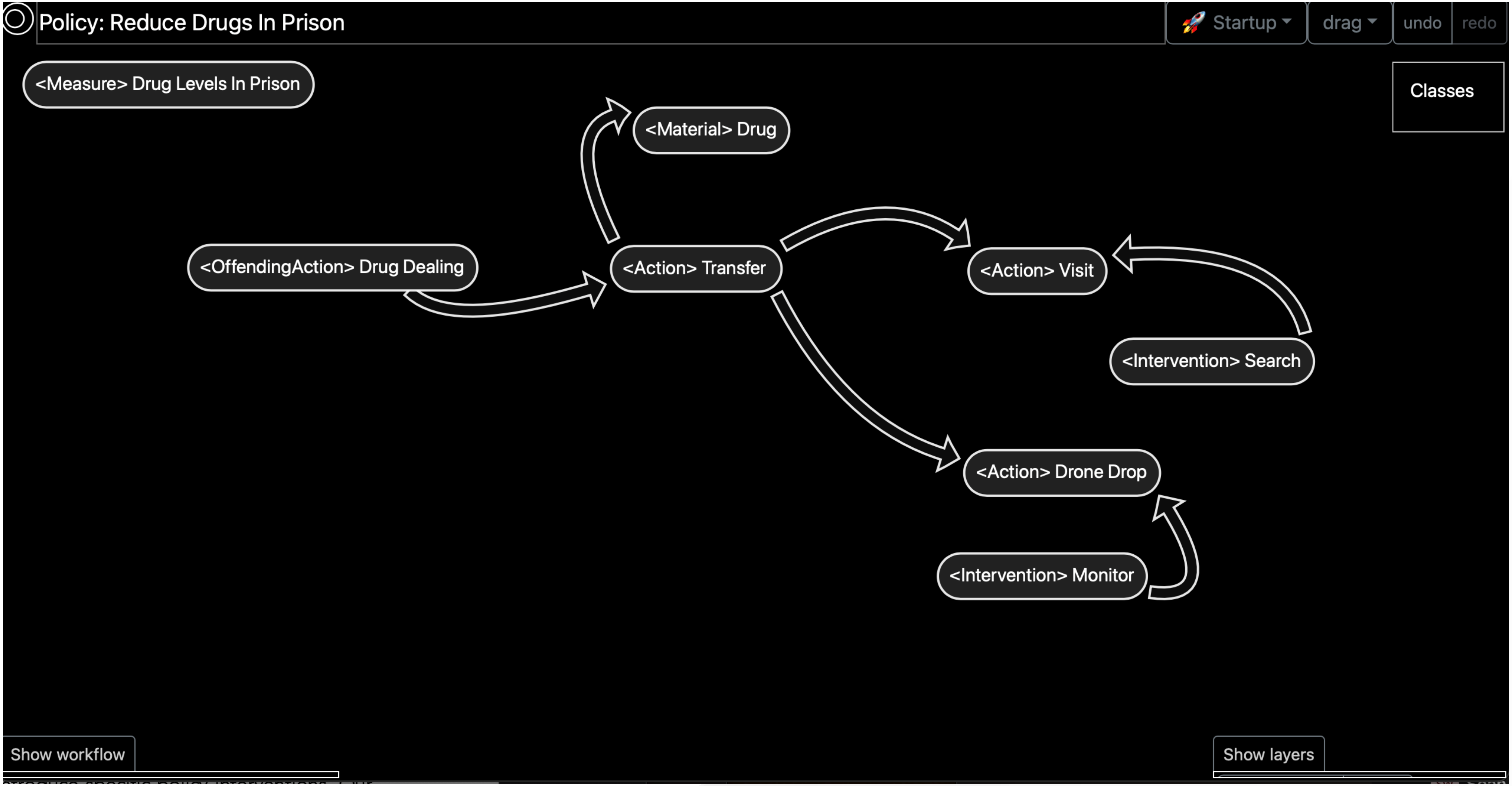
- Design of Domain Specific Modelling Language for SOC to:
  - support structured understanding of the problem
  - Ensure link to potential policy



Domain Specific Modelling Language

Policy Modelling Language





Policy: Reduce Drugs In Prison
Startup
drag
undo
redo
<Measure> Drug Levels In Prison
Classes
<Material> Drug
<OffendingAction> Drug Dealing
<Action> Transfer
<Action> Visit
<Intervention> Search
<Action> Drone Drop
<Intervention> Monitor
Show workflow
Show layers

Systems Expert

General Problem Specification Language

Systems Expert

Stakeholder

Domain Specific Modelling Language

Consultant

Stakeholder

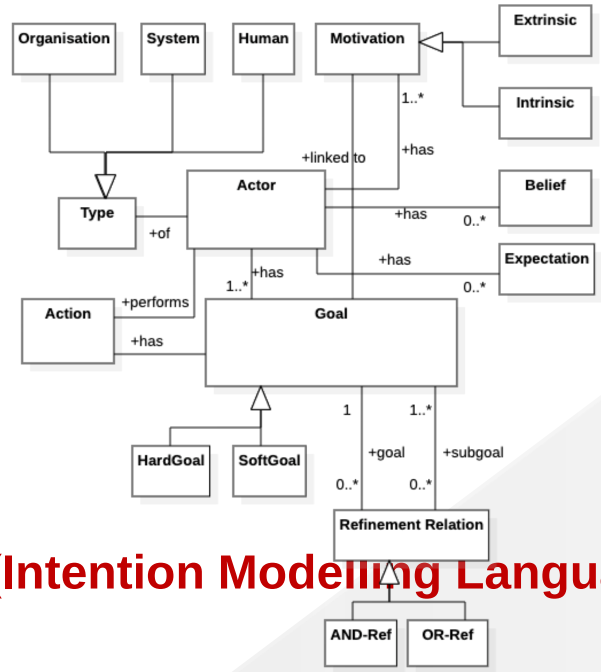
Platform Specific Modelling Language

Mappings to Tool

Policy Modelling Language

Domain Expert

Domain Expert



(Intention Modelling Language)

Addressing the gap: Methodological advances

- Methodology research is not identified as an important research gap in DT systematic reviews.
- DT Design is syncretic in its outlook. The simulation component draws upon work of Sargent and has several derivatives.
- Sargent methodology can be augmented from

— Action Research from Sociotechnical systems design.

— Policy Research: Theory of Change - rigorous yet participatory process incorporating goals, conditions and interventions that bring some desired change arranged in a causal framework

— Value sensitive design: (ongoing project in Software engineering, focussing on trade-offs and their documentation.

— Probabilistic modelling to provide guidance within probable results. (But requires education on how to interpret models.

Some difficult questions over the last year

- Any computational simulation will be a simplification of reality. In complex systems minor perturbations can have big effects. How do we know what we to ignore?
- If a sociotechnical digital twin can only be a partial model, how is margin of error built in?
- Most applications of DT are in tech/eng areas; what is the status of sociotechnical DT? Where are they being applied, and what is their level of success?
- Are DT a type of black box model, or do they allow us to understand the inner operations/actions within a system?
- The semantics of your modelling language can encode and describe complex systems, but does including too much complexity obscure understanding?
- Machine learning /AI approaches can work effectively in complex domains. Can DTs take advantage of these methods?
- Where do you locate your work in relation to other current flavours: CSS (comp soc science), ABM (agent based models), Data Science etc?
- How should optimism bias be accounted for?

Thank you for listening

Questions?

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