Foundations and Applications of Digital Twins

Prof. Dr. Istvan David

McMaster University, Canada

istvan.david@mcmaster.ca
istvandavid.com

October 15, 2024

Dr. Istvan David

AI on the farm: A new path to food self-sufficiency

UDEMNOUVELLES | 03/16/2022 | CAROLINE BOILY

Sustainability

Technological | Economic | Environmental | Social

NSERC CRSNG DGECR-2024-00293: End-to-end Sustainable Systems Engineering

IVADO Postdoctoral Laureate 2021

| modeling and simulation | digital twins for C(B)PS | digital twins and sustainability |
| engineering processes | reinforcement learning | energy-aware systems |

MSc in Business Inf. Systems (2014)
MSc in Computer Engineering (2013)
BSc in Computer Engineering (2011)
Budapest Tech (BME), Hungary

PhD in Computer Science (2014–19)
University of Antwerp, Belgium

Postdoctoral researcher (2021–2023)
Université de Montréal, Canada

Assistant Professor (2023–)
McMaster University, Canada

R&D Software Engineer (2012–2014)
Mentor Graphics, Hungary

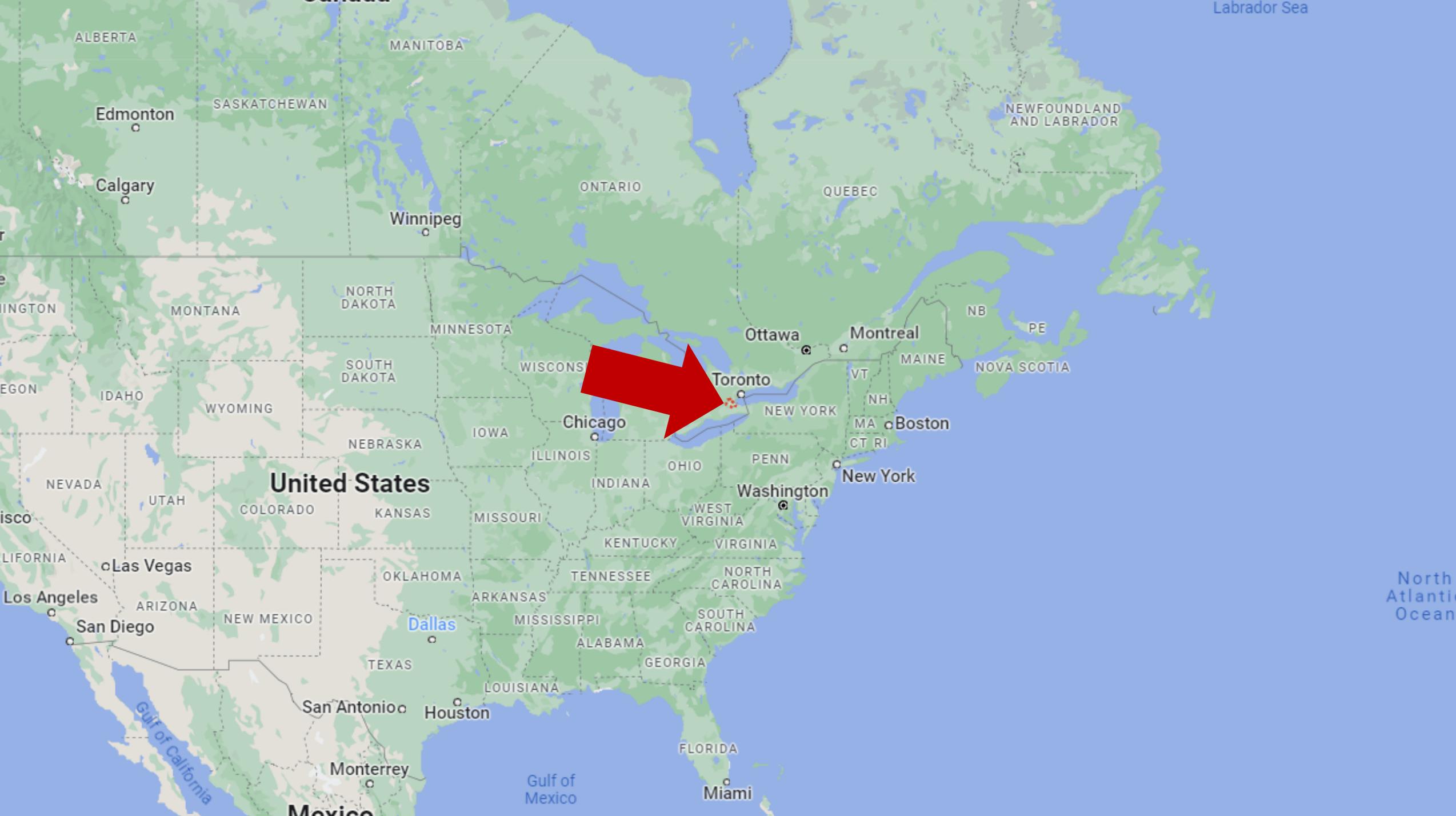Head of Digital Innovation (2019–2020)
Trigo Group, Hungary/France

McMaster University | BRIGHTER WORLD

Top-5 university in Canada
        Along with UofT, UdeM, McGill, UBC
#1 world-wide in industry impact (THE'23)
#1 in Canada in research quality (THE'23)
#1 in Canada in research intensity
Top-35 in THE'22 impact rankings

~40.000 students
        34.000 undergrad, 6.000 grad
18% international from 125 countries
        Grad: 30% international
Undergrad admission average ~90%

~1000 faculty members (17000 employees)
        110+ endowed chairs, 15 endw. Profs.
        90 Canada Research Chairs
Research intensity ~$420k/faculty
One of Canada's best diversity employers

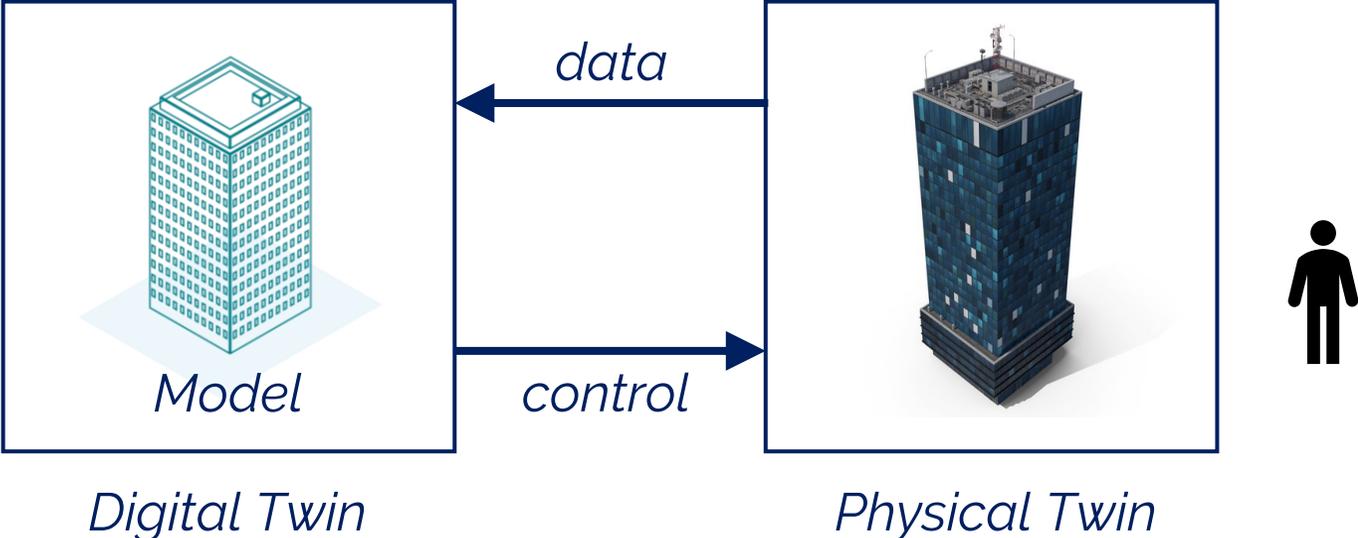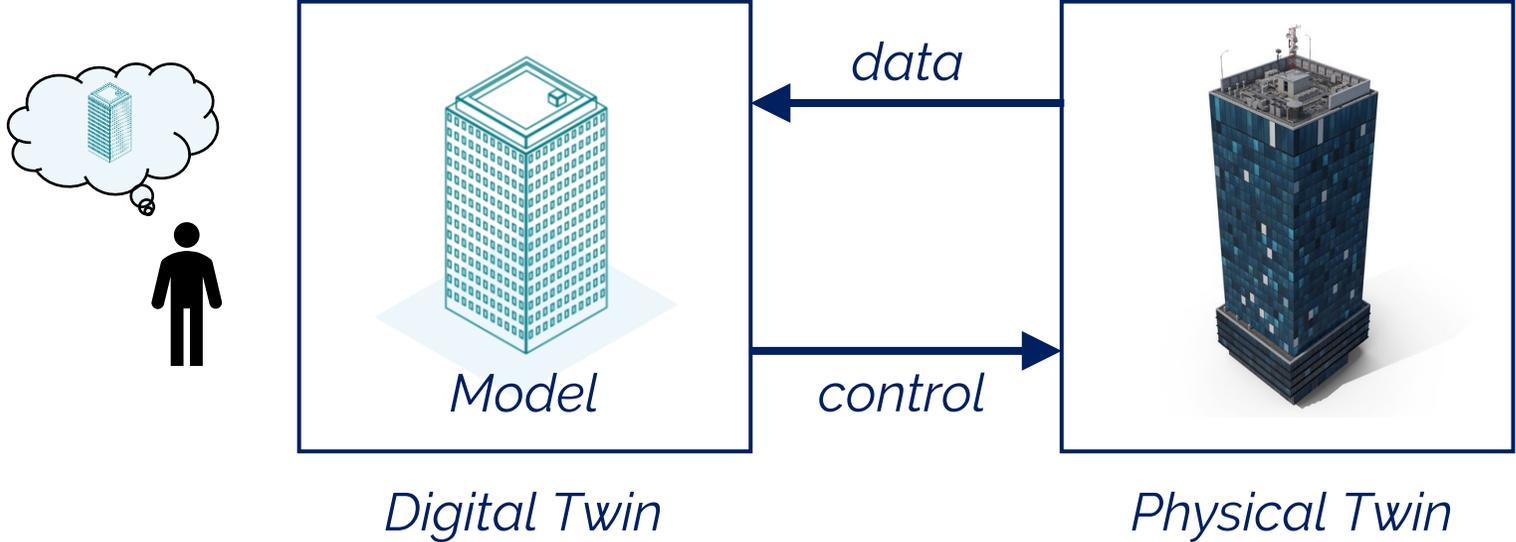# Digital twins

Digital twinning

Physical Twin

Digital twinning

Model

Digital Twin

Physical Twin

data

control

Digital twinning

Model

Digital Twin

data

control

Physical Twin

Digital twinning

data

control

Model

Digital Twin

Physical Twin

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T$$

Digital twinning

data

control

Model

Digital Twin

Physical Twin

Digital "X"

Verdouw et al., 2021

A. IMAGINARY DIGITAL TWIN

B. MONITORING DIGITAL TWIN

C. PREDICTIVE DIGITAL TWIN

D. PRESCRIPTIVE DIGITAL TWIN

E. AUTONOMOUS DIGITAL TWIN

F. RECOLLECTION DIGITAL TWIN
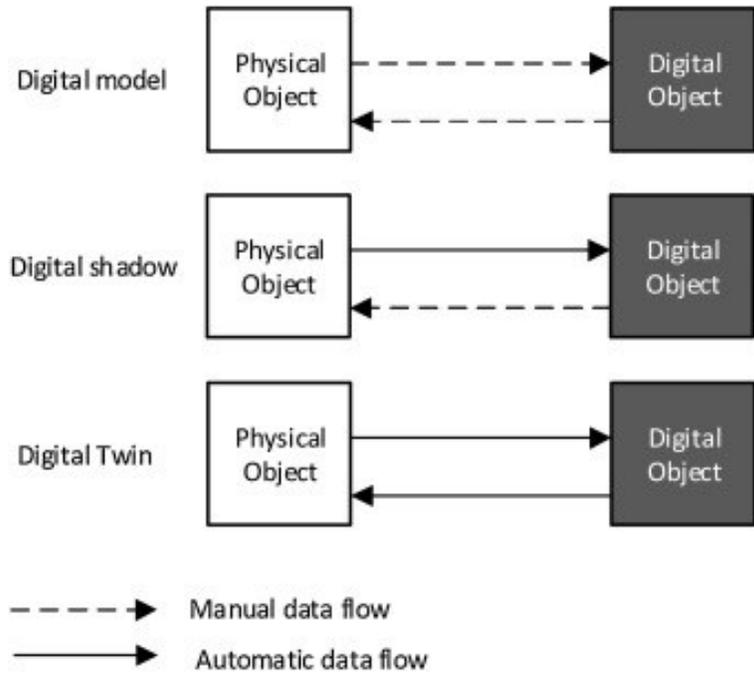
Kritzinger et al., 2018

A DEVS-based engine for building digital quadruplets

Daniella Niyonkuru and Gabriel Wainer

$$C_{i,j}^t = conc - 20 \left(\frac{0.375}{\nabla_x} (C_{i,j}^t - C_{i-1,j}^t) - \frac{16}{\nabla_x{}^2} (C_{i+1,j}^t - 2C_{i,j}^t + C_{i-1,j}^t) \right)$$

$$C_{i,j}^{t+1} = C_{i,j}^t - 20 \left(\frac{0.375}{\nabla_y} (C_{i,j}^{t+1} - C_{i,j-1}^{t+1}) - \frac{16}{\nabla_y{}^2} (C_{i,j+1}^{t+1} - 2C_{i,j}^{t+1} + C_{i,j-1}^{t+1}) \right) + 20 (S^*)$$

(a) (b) (c) (d)

14
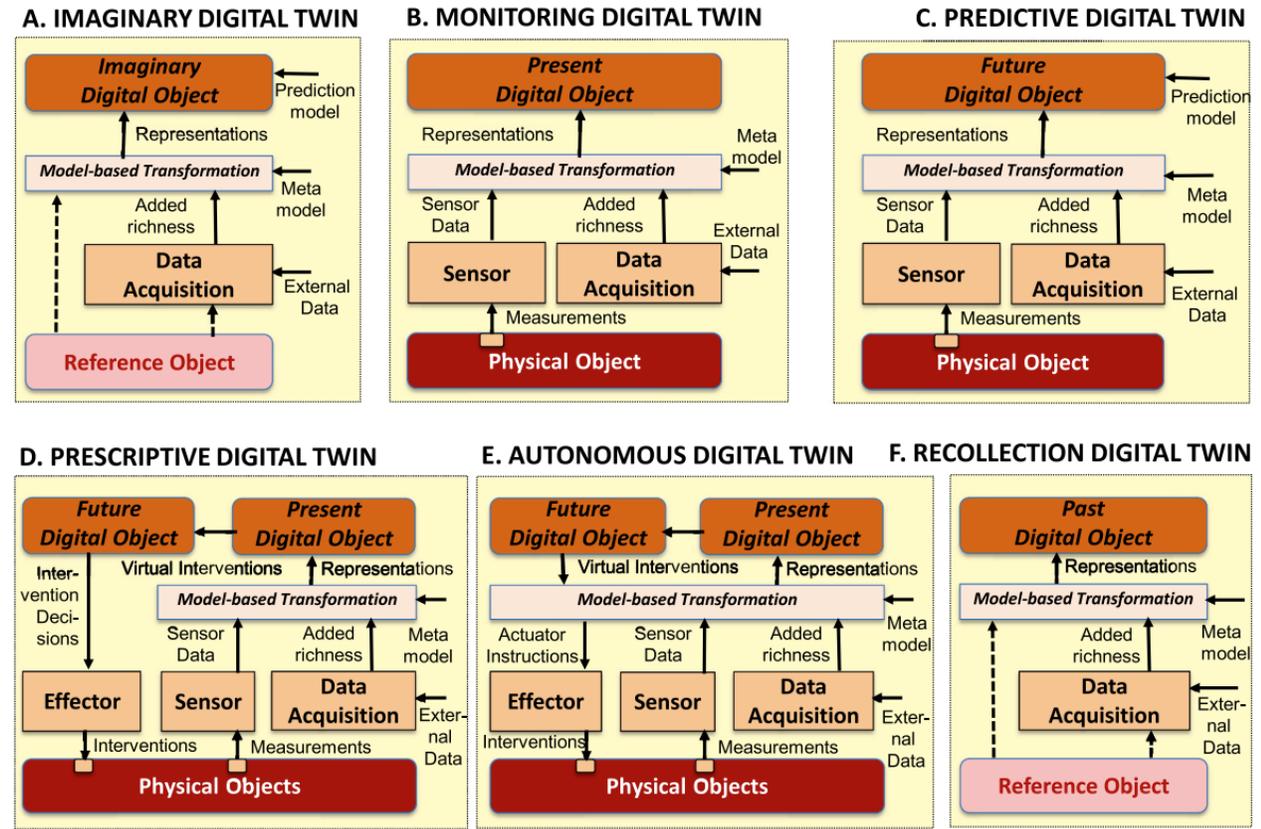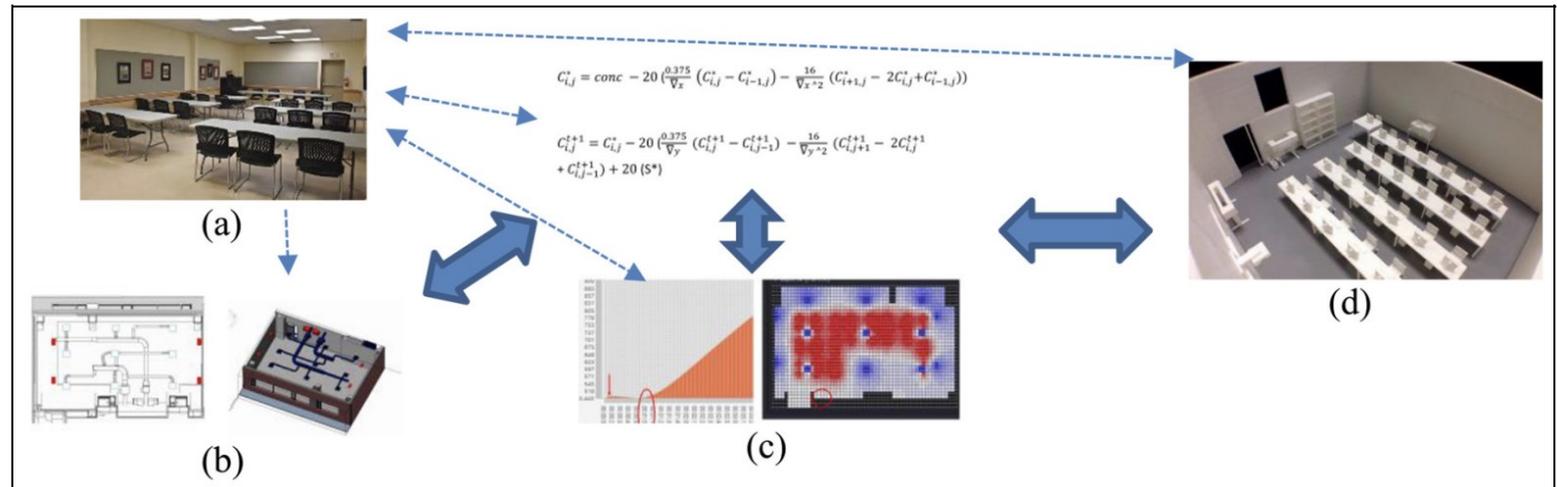
Digitalization and digital transformation

Industry 4.0 and 5.0

I5.0 complements the existing I4.0 approach by specifically putting research and innovation at the service of the transition to a **sustainable, human-centric** and **resilient European industry**

European Commission

Digital Transformation Pyramid

Digital
Transformation
Digitalization
Digitization

VISION, EXPERIENCE, ANSWERS FOR INDUSTRY, INFRASTRUCTURE & CITIES

© ARC Advisory Group •

Nominal GDP driven by digitally transformed and other enterprises worldwide from 2018 to 2023

GDP in trillion U.S. dollars

Year	Digitally transformed enterprises	Other enterprises
2018	13.5	67.7
2020	23.2	62.8
2022	44.6	52.3
2023*	53.3	49.1

● Digitally transformed enterprises ● Other enterprises

https://www.statista.com/statistics/1134766/nominal-gdp-driven-by-digitally-transformed-enterprises/

2018

Gartner Hype Cycle for Emerging Technologies, 2018.

Technologies shown on the curve include: Digital Twin, Biochips, Smart Workspace, Brain-Computer Interface, Autonomous Mobile Robots, Smart Robots, Deep Neural Network ASICs, AI PaaS, Quantum Computing, 5G, Volumetric Displays, Self-Healing System Technology, Conversational AI Platform, Autonomous Driving Level 5, Edge AI, Exoskeleton, Blockchain for Data Security, Knowledge Graphs, 4D Printing, Artificial General Intelligence, Smart Dust, Flying Autonomous Vehicles, Biotech — Cultured or Artificial Tissue, Deep Neural Nets (Deep Learning), Carbon Nanotube, IoT Platform, Virtual Assistants, Silicon Anode Batteries, Blockchain, Connected Home, Autonomous Driving Level 4, Mixed Reality, Neuromorphic Hardware, Smart Fabrics, Augmented Reality.

Phases: Innovation Trigger, Peak of Inflated Expectations, Trough of Disillusionment, Slope of Enlightenment, Plateau of Productivity.

As of August 2018

Plateau will be reached:
○ less than 2 years ○ 2 to 5 years ● 5 to 10 years △ more than 10 years ⊗ obsolete before plateau

Gartner Hype Cycle for Emerging Technologies, 2019

Expectations (y-axis)

Time (x-axis)

Biochips
AI PaaS
Edge Analytics
Autonomous Driving Level 5
Low-Earth-Orbit Satellite Systems
Edge AI
Explainable AI
Personification
Knowledge Graphs
Synthetic Data
Light Cargo Delivery Drones
Transfer Learning
Flying Autonomous Vehicles
Augmented Intelligence
Nanoscale 3D Printing
Decentralized Autonomous Organization
DigitalOps
Generative Adversarial Networks
Adaptive ML
Decentralized Web
AR Cloud
Immersive Workspaces
Biotech - Cultured or Artificial Tissue
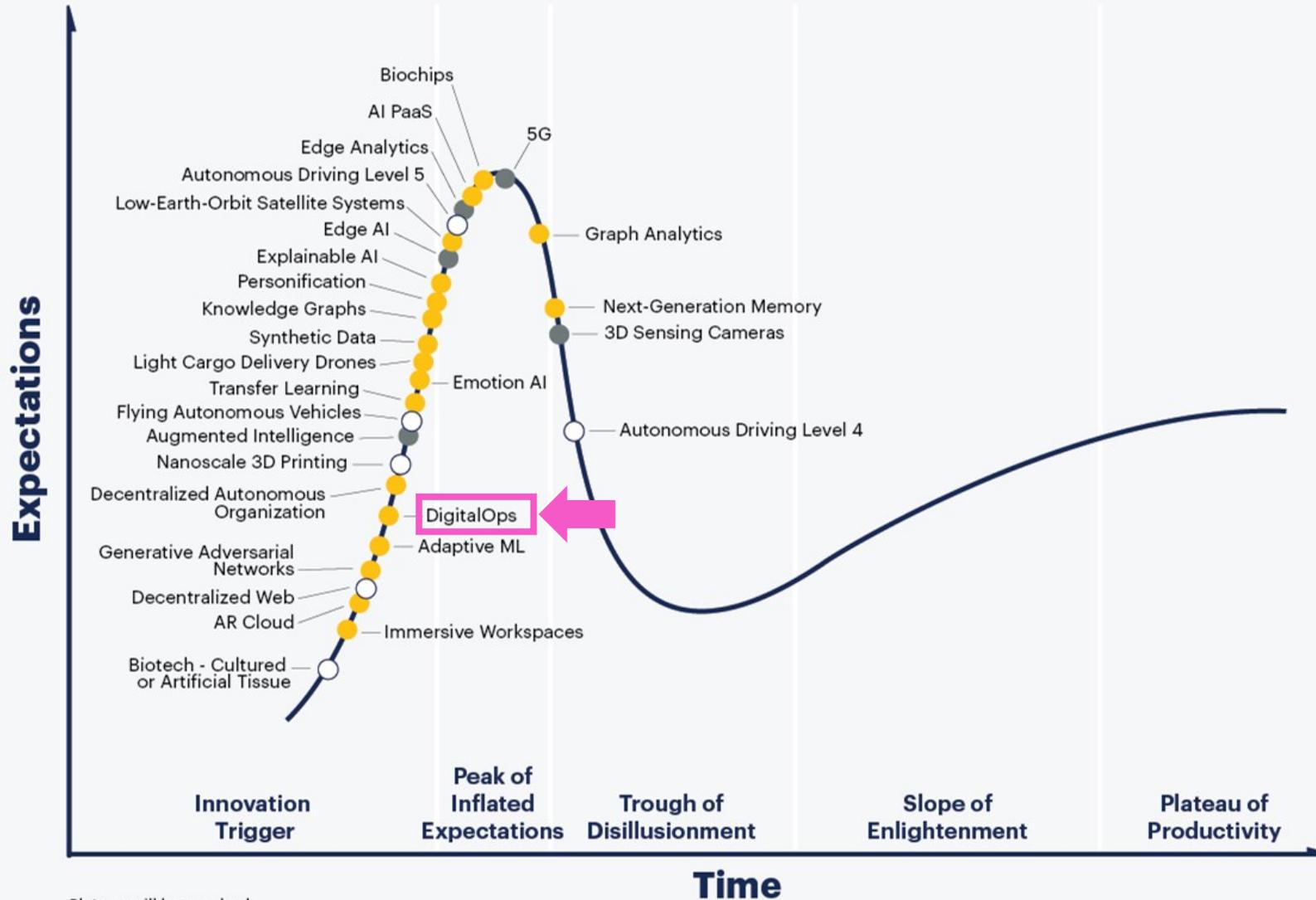
5G
Graph Analytics
Next-Generation Memory
3D Sensing Cameras
Emotion AI
Autonomous Driving Level 4

Innovation Trigger | Peak of Inflated Expectations | Trough of Disillusionment | Slope of Enlightenment | Plateau of Productivity

Plateau will be reached:

○ less than 2 years   ● 2 to 5 years   ● 5 to 10 years   ○ more than 10 years   ● obsolete before plateau

As of August 2019

Hype Cycle for Emerging Technologies, 2020

Expectations

Secure Access Service Edge (SASE)
Social Distancing Technologies
Embedded AI
Data Fabric
Explainable AI
Composable Enterprise
AI Augmented Development
Carbon-Based Transistors
Responsible AI
Multiexperience
Digital Twin of the Person
Citizen Twin
Packaged Business Capabilities
Generative AI
Bring Your Own Identity
Composite AI
Adaptive ML
Social Data
Private 5G
Generative Adversarial Networks
Differential Privacy
Biodegradable Sensors
2-Way BMI (Brain Machine Interface)
Ontologies and Graphs
Health Passport
Self-Supervised Learning
Low-Cost Single-Board Computers at the Edge
DNA Computing and Storage
AI-Assisted Design
Authenticated Provenance

Innovation Trigger   **Peak of Inflated Expectations**   **Trough of Disillusionment**   **Slope of Enlightenment**   **Plateau of Productivity**

Time

Plateau will be reached:

○ less than 2 years   ● 2 to 5 years   ● 5 to 10 years   ▲ more than 10 years   ⊗ obsolete before plateau   As of July 2020
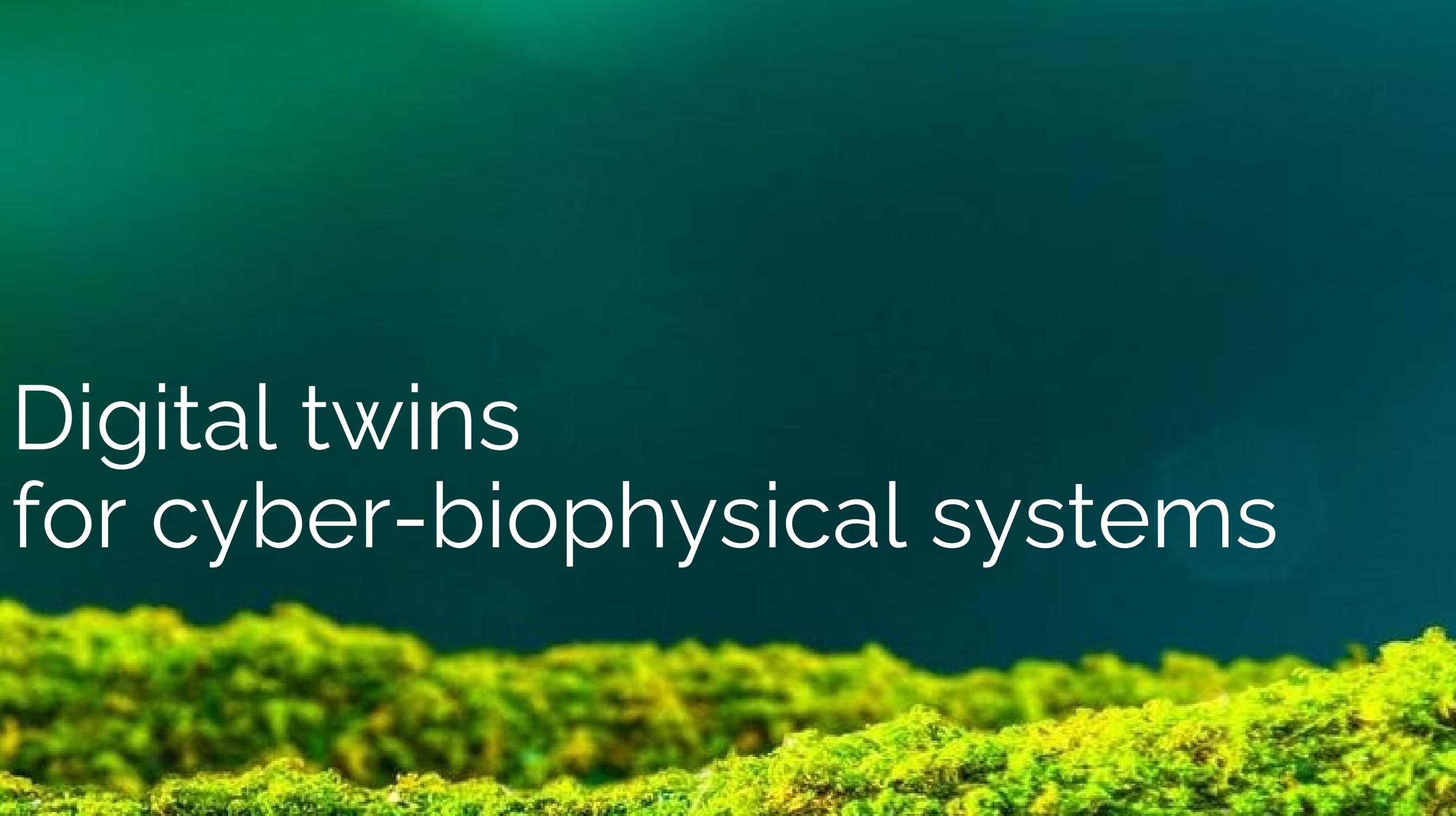
Hype Cycle for Emerging Technologies, 2021

Hype Cycle for Emerging Tech, 2022

Expectations

- Foundation Models
- Web3
- Computational Storage
- Superapps
- Industry Cloud Platforms
- Internal Talent Marketplaces
- Decentralized Identity
- NFT
- Cloud Data Ecosystems
- Digital Humans
- Dynamic Risk Governance
- Observability-Driven Development
- Cloud Sustainability
- Data Observability
- Platform Engineering
- Causal AI
- Metaverse
- Open Telemetry
- Minimum Viable Architecture
- Augmented FinOps
- Digital Twin of a Customer
- Machine Learning Code Generation
- Generative Design AI
- Autonomic Systems
- Cybersecurity Mesh Architecture

Innovation Trigger · **Peak of Inflated Expectations** · **Trough of Disillusionment** · **Slope of Enlightenment** · **Plateau of Productivity**

Time

Plateau will be reached:

○ less than 2 years ● 2 to 5 years ● 5 to 10 years ▲ More than 10 years ⊗ Obsolete before plateau

As of August 2022

Digital twins
for cyber-biophysical systems

Prevalence of Household Food Insecurity by Province, 2021

14.9%

20.3%

18.8%

17.8%

16.1%

13.1%

17.9%

15.3%

17.7%

19.0%

Data Source: Statistics Canada, Canadian Income Survey (CIS) 2020. Data on the territories from this survey not available yet.
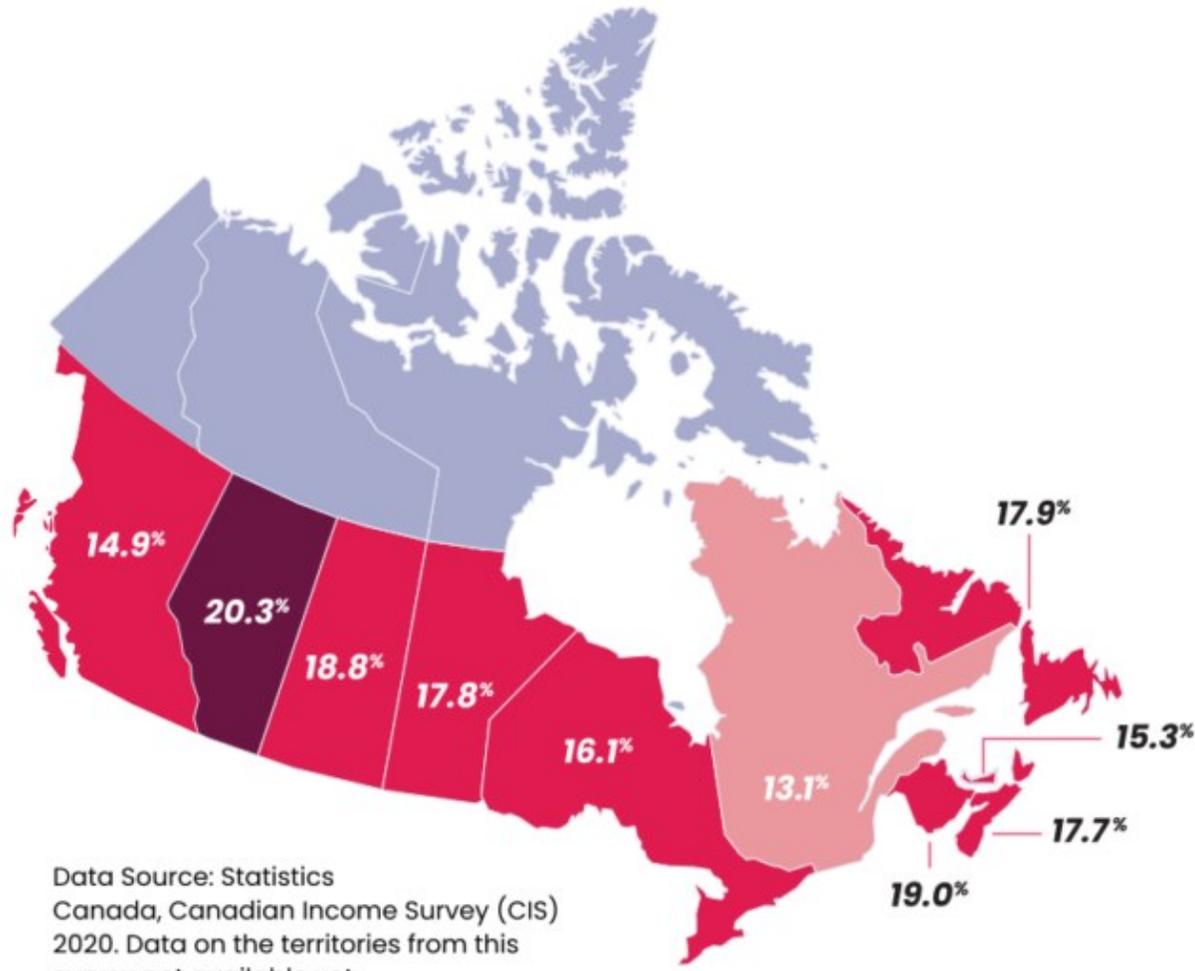
The Global State of Food Security

Best and worst performing countries for food security in 2020*

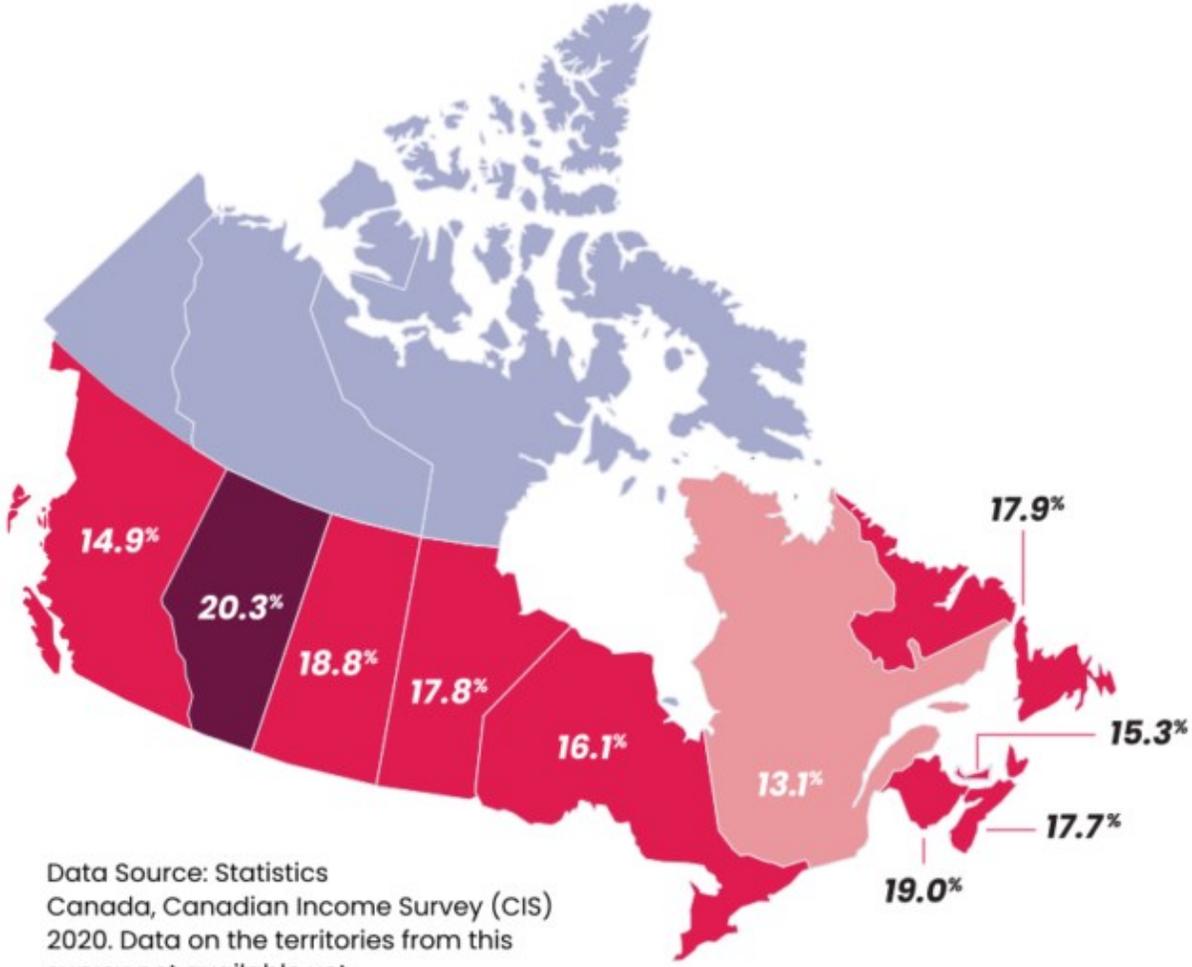■ Best performance   ■ Good performance
■ Moderate performance   ■ Need improvement
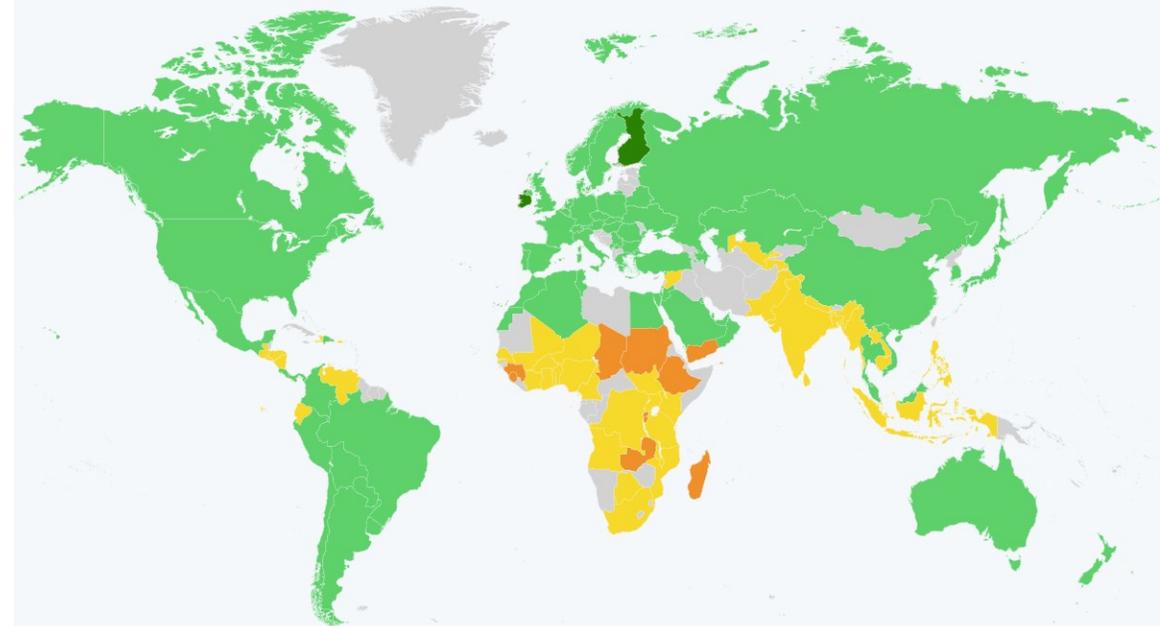
* Affordability, availability, safety, quality and natural resources of food based on 59 unique indicators across 113 countries.

Source: Economist Intelligence Unit

Prevalence of Household Food Insecurity by Province, 2021

Data Source: Statistics Canada, Canadian Income Survey (CIS) 2020. Data on the territories from this survey not available yet.

14.9%
20.3%
18.8%
17.8%
16.1%
13.1%
17.9%
15.3%
17.7%
19.0%

McMaster University

Controlled Environment Agriculture (CEA)
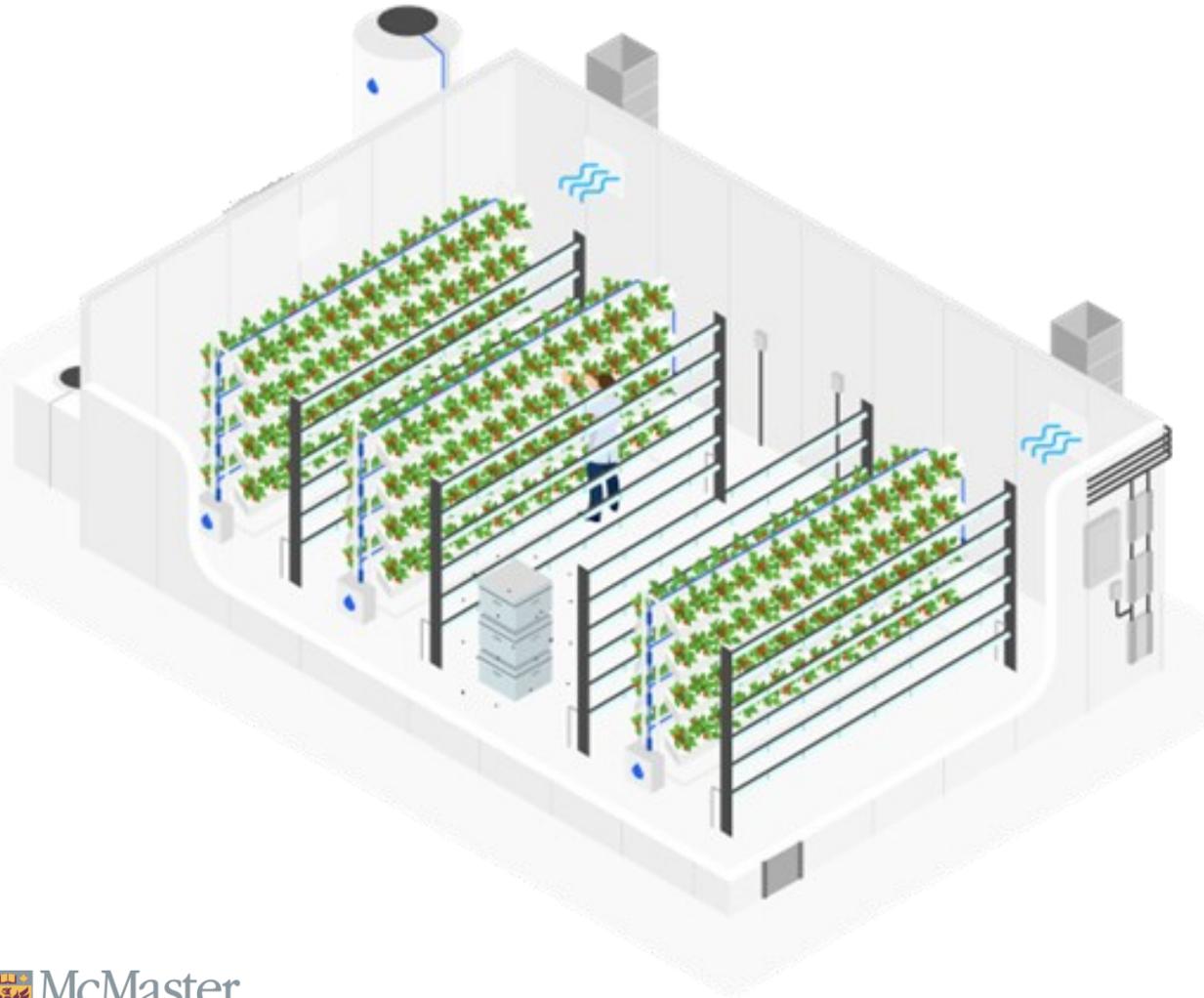
The challenge of CEA: **control is hard**

Maximize crop-to-energy ratio
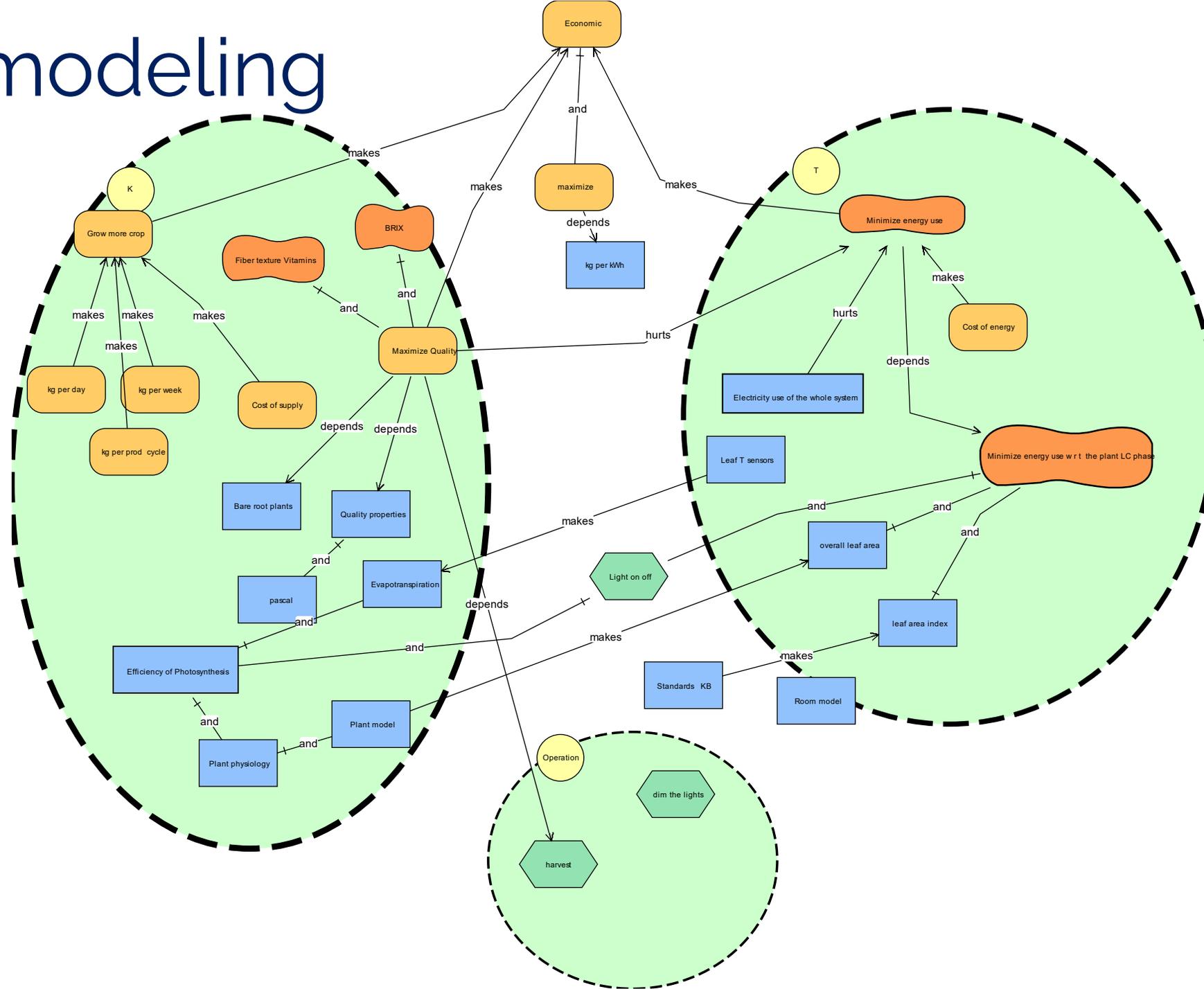*Reduce waste*
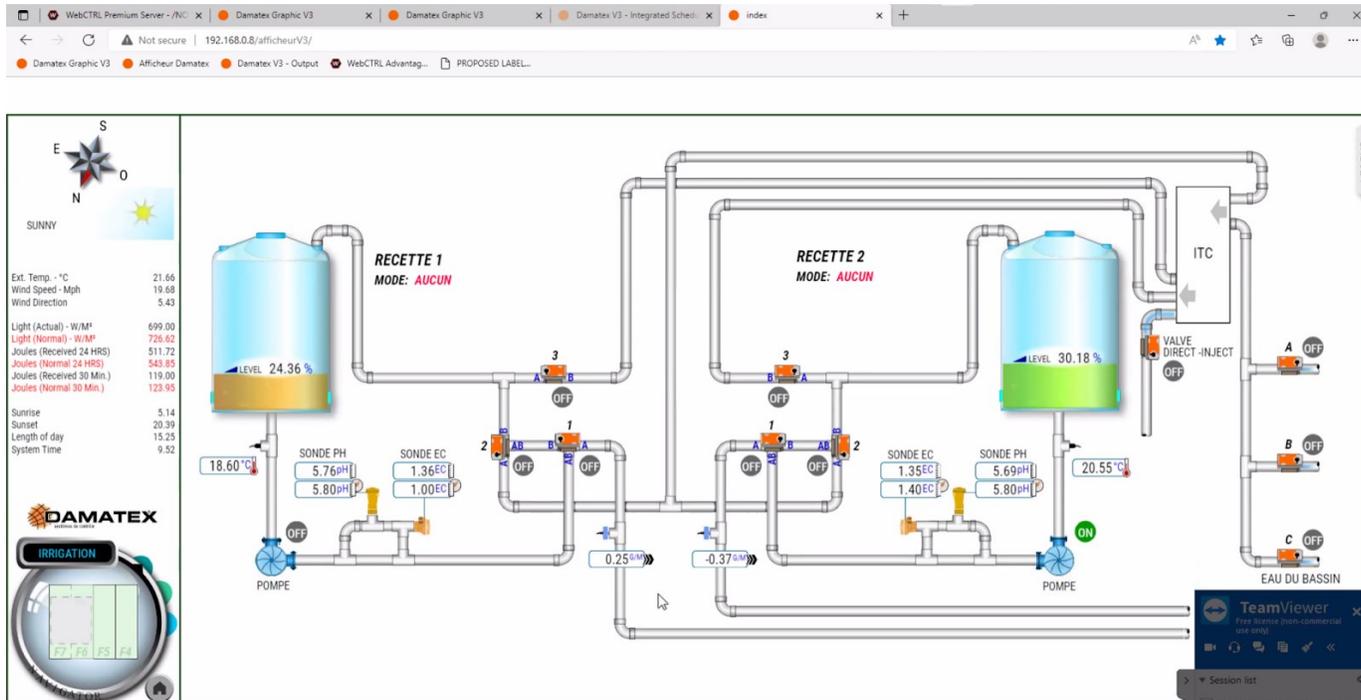
...

Each bush must produce 50 grams of 🍓 per week
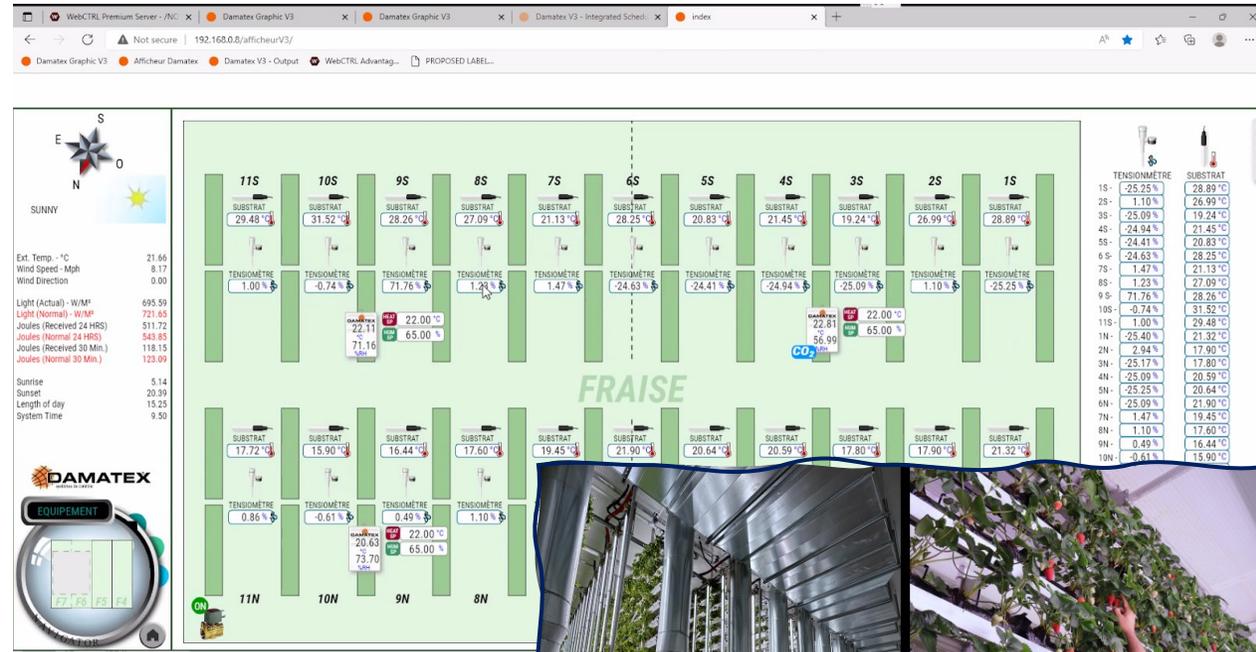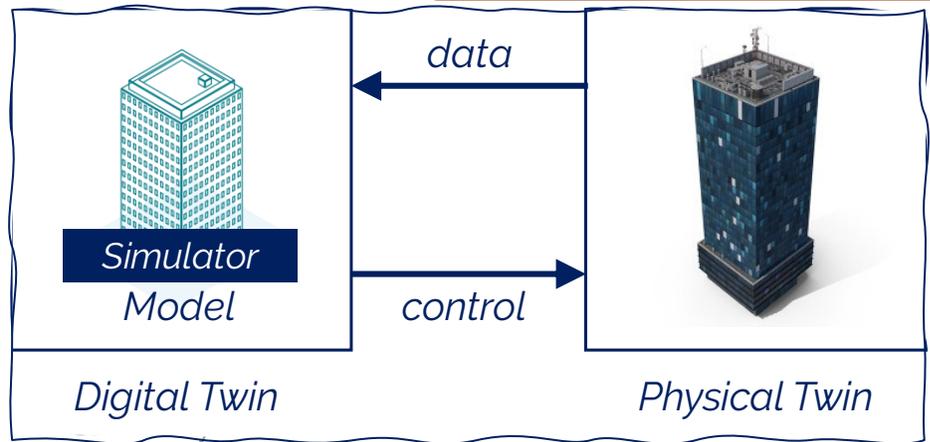   *...starting two months from now*

Expressing expert processes

Goal modeling

Models
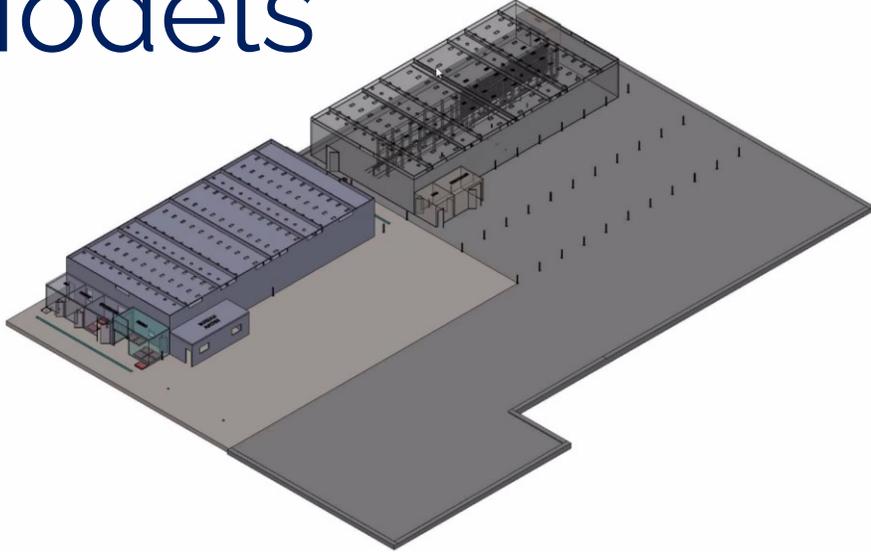
DT4CBPS: Conceptual framework and requirements
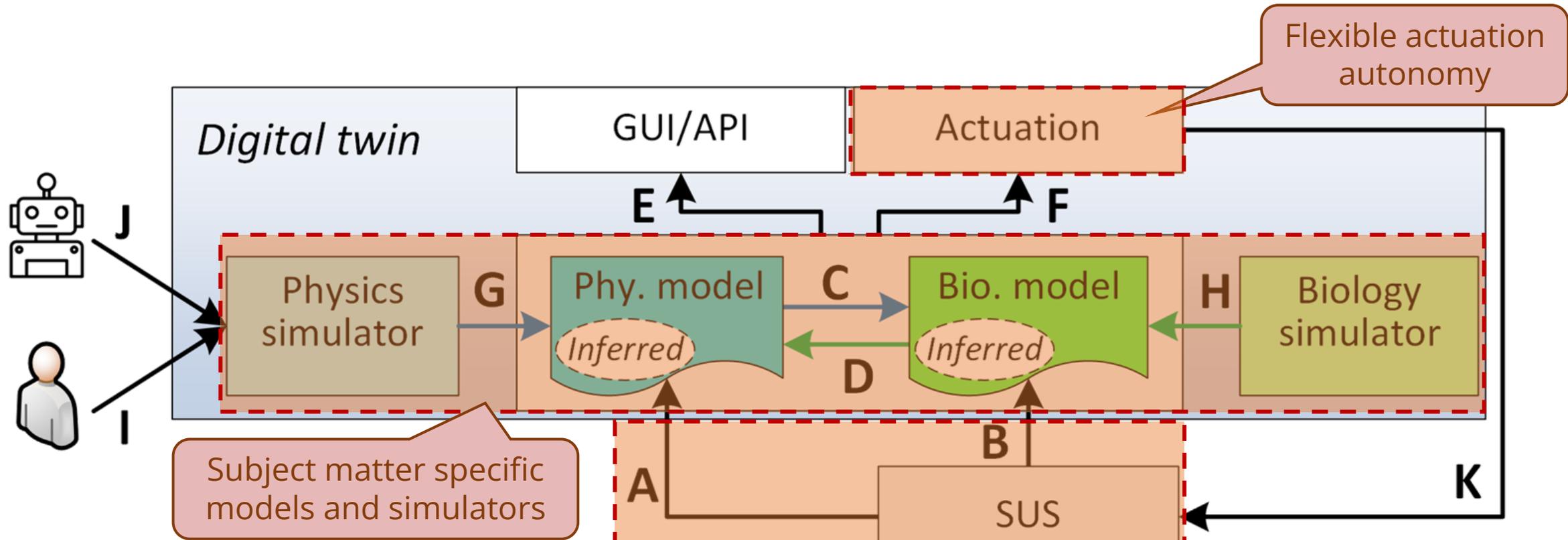
Negri, E., Fumagalli, L., Cimino, C. and Macchi, M.
FMU-supported simulation for CPS digital twin.
Procedia manufacturing: 28, pp.201-206, 2019.

$$\frac{dy}{dt} = ky$$
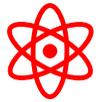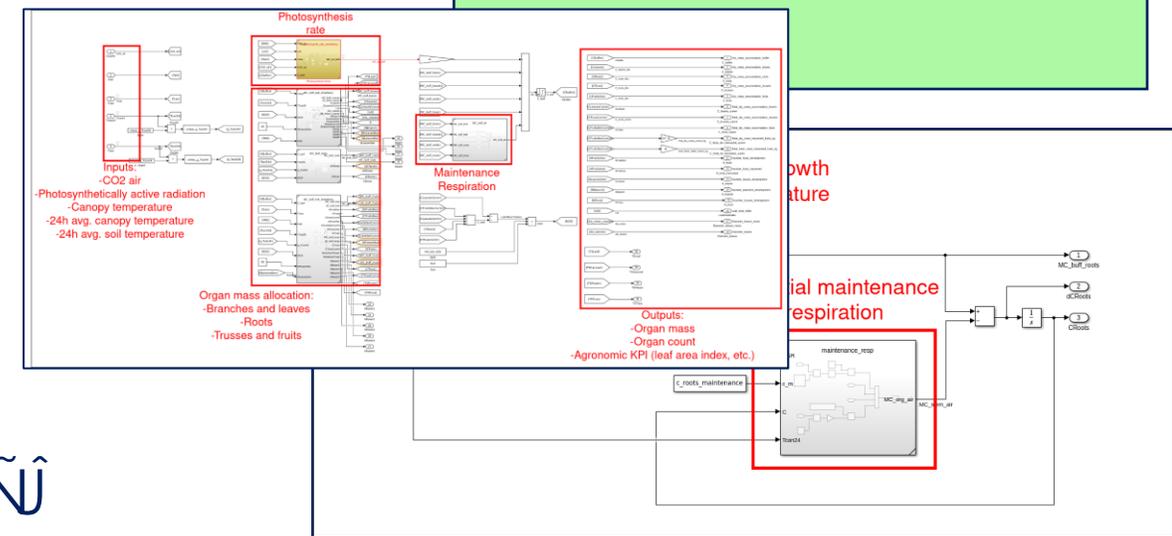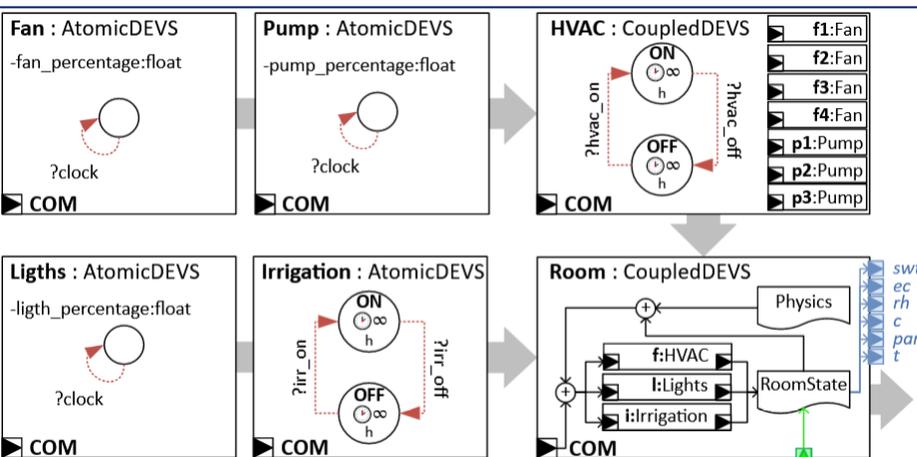
Digital Twins for Cyber-Biophysical Systems: Challenges and Lessons Learned

Istvan David[*], Pascal Archambault[*], Quentin Wolak[*], Cong Vinh Vu[*],
Timothé Lalonde[†], Kashif Riaz[†], Eugene Syriani[*], Houari Sahraoui[*]
[*]DIRO, Université de Montréal, Canada – {firstname.lastname}@umontreal.ca
[†]Ferme d'Hiver Technologies, Canada – {tlalonde,kriaz}@fermedhiver.ca

ACM/IEEE 26th International Conference on
Model-Driven Engineering Languages and Systems

BEST PRACTICE TRACK PAPER

Digital Twins for Cyber-Biophysical Systems:
Challenges and Lessons Learned

Istvan David, Pascal Archambault, Quentin Wolak, Cong Vinh Vu,
Timothé Lalonde, Kashif Riaz, Eugene Syriani and Houari Sahraoui

G. Taentzer
PC Chair

T. Kühne
PC Chair

A. Cicchetti
General Chair

A. Pierantonio
General Chair

Challenges

- Design and operation
- Siloed subsystems
- Manual collection
- Intrusive measurements
- Data
- Interference creates noise
- Tool-dependence
- Modeling and Simulation
- Wide stakeholder gap
- Untested hypotheses
- Manual modeling not feasible
- No reusability
- Lack of explainability
- No full autonomy
- Actuation
- Fidelity is questionable

Lessons learned

- Domain-augmented languages
- Collaborative model-based reasoning
- Data-driven techniques offer limited upside
- Instrumentation to be addressed early on
- Testing and calibration are challenging
- Proper test coverage for frequent refactoring
- Early frequent user acceptance testing
- Deployment/operation require support

McMaster University

AI on the farm: A new path to food self-sufficiency

UDEMNOUVELLES | 03/16/2022 | CAROLINE BOILY

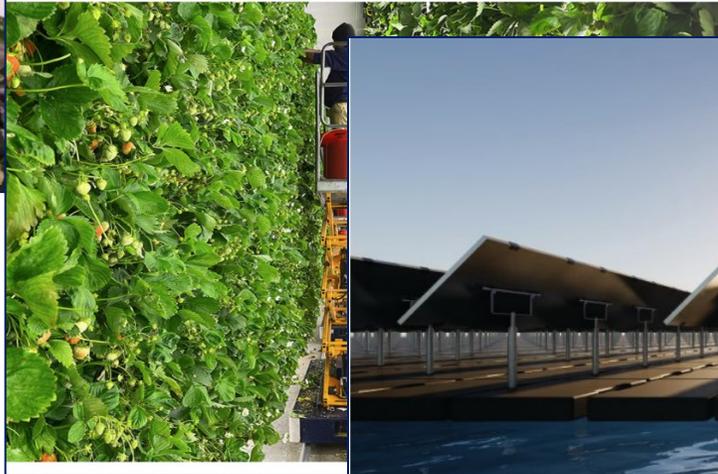https://nouvelles.umontreal.ca/en/article/2022/03/16/ai-on-the-farm-a-new-path-to-food-self-sufficiency/

Des algorithmes pour transformer l'agriculture hivernale

L'intelligence artificielle s'invite dans fermes verticales de l'entreprise québécoise Ferme d'hiver, qui ambitionne de proposer une solution de rechange technologique et carboneutre à l'importation de fruits et légumes pendant la saison froide.

https://lactualite.com/techno/des-algorithmes-pour-transformer-lagriculture-hivernale/

https://mydigitalpublication.com/publication/?m=1281&i=805712&p=22&ver=html5

What the future brings

Exploring sustainable solutions for greenhouse adaptation and survival

McMaster University

33

AI Simulation by Digital Twins

Hype Cycle for Artificial Intelligence, 2023

AI Simulation
The combined application of AI and simulation technologies to jointly develop AI agents and the simulated environments in which they can be trained, tested and sometimes deployed.

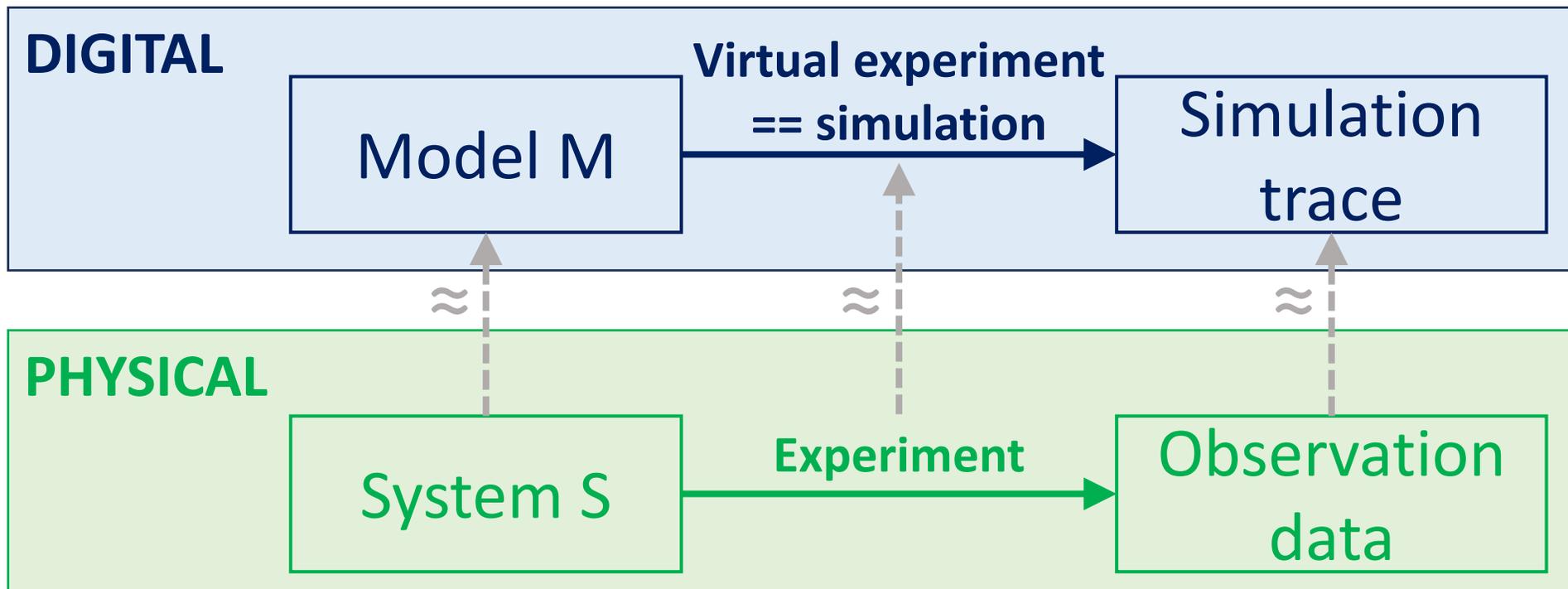Some of the best simulators today: in DTs

Xiaoran (Sharon) Liu

- Xiaoran Liu and Istvan David. "AI Simulation by Digital Twins: Systematic Survey of the State of the Art and a Reference Framework". In: ACM/IEEE MODELS-C / EDTConf'24. ACM, 2024.
- Xiaoran Liu and Istvan David. "AI Simulation by Digital Twins: Reference Framework and Mapping on ISO 23247". In: Soft. Syst. Model. Springer. 2024. [Under review]

Opportunity:
purposeful experimentation to acquire missing data

DIGITAL

Model M → **Virtual experiment == simulation** → Simulation trace

PHYSICAL

System S → **Experiment** → Observation data

Based on:
- B. P. Zeigler and T. I. Oren, "Theory of Modelling and Simulation," 1979,
- H. Vangheluwe et al. "An introduction to multi-paradigm modelling and simulation." 2002.

McMaster University

Domains/problems

Digital twins

AI/ML

Lifecycle models

Challenges/limitations

AI Simulation by Digital Twins
Systematic Survey of the State of the Art and a Reference Framework

Xiaoran Liu
McMaster University
Hamilton, Canada
liu2706@mcmaster.ca

Istvan David
McMaster University
Hamilton, Canada
istvan.david@mcmaster.ca

ABSTRACT

Insufficient data volume and quality are particularly pressing challenges in the adoption of modern subsymbolic AI. To alleviate these challenges, AI simulation recommends developing virtual training environments in which AI agents can be safely and efficiently developed. Digital twins open new avenues in AI simulation, as these high-fidelity virtual replicas of physical systems are equipped with state-of-the-art simulators and the ability to further interact with the physical system for additional data collection. In this paper, we report on our systematic survey of digital twin-enabled AI simulation. By analyzing 22 primary studies, we identify technological trends and derive a reference framework to situate digital twins and AI components. Finally, we identify challenges and research opportunities for prospective researchers.

CCS CONCEPTS

• General and reference → Surveys and overviews; • Computing methodologies → Learning settings.

KEYWORDS

AI, artificial intelligence, data science, deep neural networks, digital twins, lifecycle model, machine learning, neural networks, reinforcement learning, SLR, subsymbolic AI, survey, training

1 INTRODUCTION

Modern artificial intelligence (AI) is enabled by massive volumes of data processed by powerful computational methods [84]. This is a stark contrast with traditional AI, which is supported by symbolic methods and logic [69]. The volume and quality of available data to train AI is the cornerstone of success in modern AI. However, accessing and harvesting real-world data is a substantial barrier due to its scarcity, cost, or difficult accessibility, hindering the development of precise and resilient AI models. For example, in manufacturing,

proprietary data, data silos, and sensitive operational procedures complicate the acquisition of data [43]. Data-related barriers, in turn, limit the applicability of otherwise powerful AI methods.

AI simulation is a prime candidate for alleviating these problems. As defined by Gartner recently, AI simulation is the technique of "*the combined application of AI and simulation technologies to jointly develop AI agents and the simulated environments in which they can be trained, tested and sometimes deployed. It includes both the use of AI to make simulations more efficient and useful, and the use of a wide range of simulation models to develop more versatile and adaptive AI systems*" [47]. After modeling the phenomenon or system at hand, a simulation of the model computes the dynamic input/output behavior [77], representative of the system. A simulation produces data, called the simulation trace, that represents the behavior of the simulated system over time. These traces can be used as training data for AI agents, assuming that the simulation is a faithful, valid and detailed representation of the modeled system, and that the simulation can still be executed efficiently and in a timely manner.

With the emergence of digital twins (DT) [54], the quality attributes of simulators have improved as well. Simulators are first-class components of DTs [36] and enablers of sophisticated services, e.g., real-time adaptation [73], predictive analytics [62], and process control in manufacturing [28]. These advanced services require well-performing and high-fidelity simulators—the types of simulators that align well with the goals of AI simulation.

A recent interview study on DTs with nineteen academic and industry participants by Muctadir et al. [58] mentions that "*machine learning and reinforcement learning could possibly be combined with DTs in the future, to help to learn about complex systems (i.e., safety-critical systems) in a virtual environment, when this is difficult to do on the real-world system.*" Similar ambitions have been identified by Mihai et al. [56] as future prospects of DTs. Indeed, the improvements in simulator engineering that have been driven by DTs, are generating interest in DTs for AI simulation. It is plausible to anticipate that the next generation of AI simulation techniques will be heavily influenced by the further advancements of DT technology [51, 66]. Therefore, it is important to understand the state of affairs in digital twinning for AI simulation purposes, prepare for the related challenges, and set targeted research agendas.

This work marks a step towards converging AI simulation and DT technology. We review the state of the art on AI simulation by DTs, derive a framework, identify trends in system organization, AI flavors, and simulation, and outline future avenues of research.

Context and scope. In this work, we focus on **AI simulation by digital twins**. We acknowledge the utility of the other direction, i.e., simulators of DTs being enabled by AI [55]; however, we consider such works outside the scope of the current study.
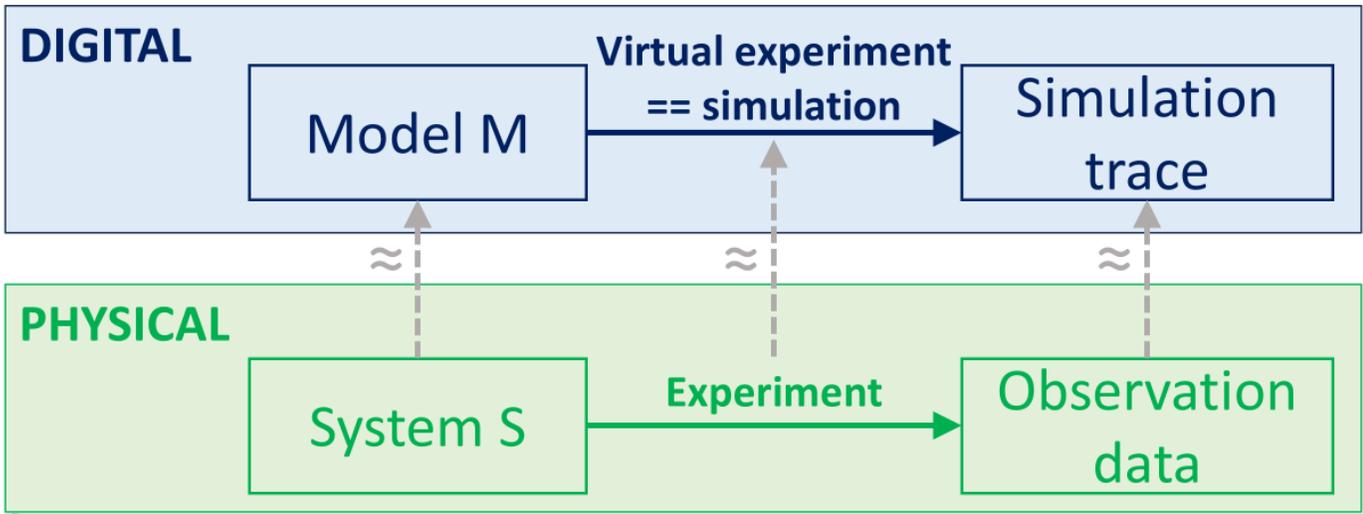
DT4AI Reference framework

Domains/problems
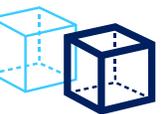
Digital twins

AI/ML

Lifecycle models

Challenges/limitations

Opportunity:
purposeful experimentation to acquire missing data

DIGITAL

Model M → **Virtual experiment == simulation** → Simulation trace

≈   ≈   ≈

PHYSICAL

System S → **Experiment** → Observation data

Based on:
- B. P. Zeigler and T. I. Oren, "Theory of Modelling and Simulation," 1979,
- H. Vangheluwe et al. "An introduction to multi-paradigm modelling and simulation." 2002.
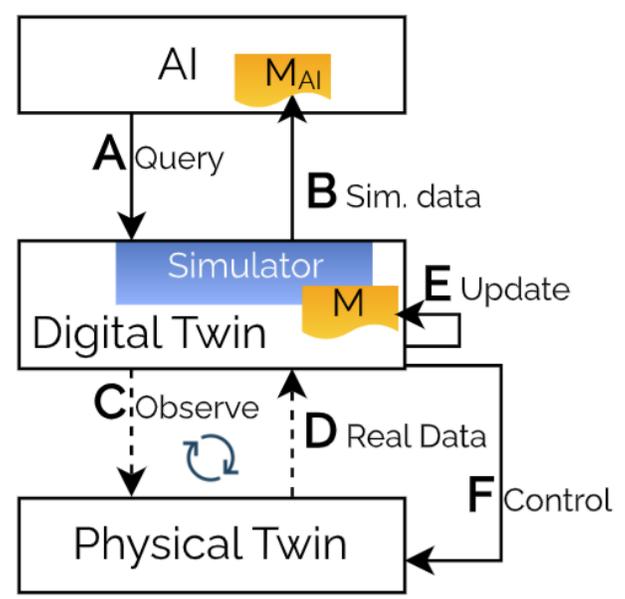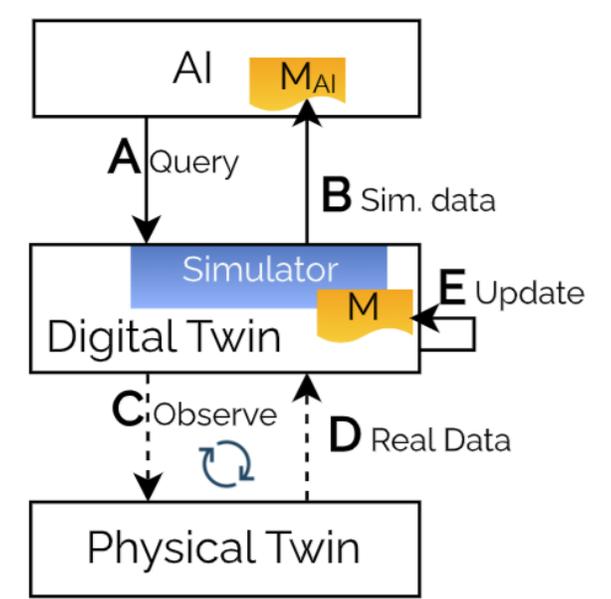
System

McMaster University
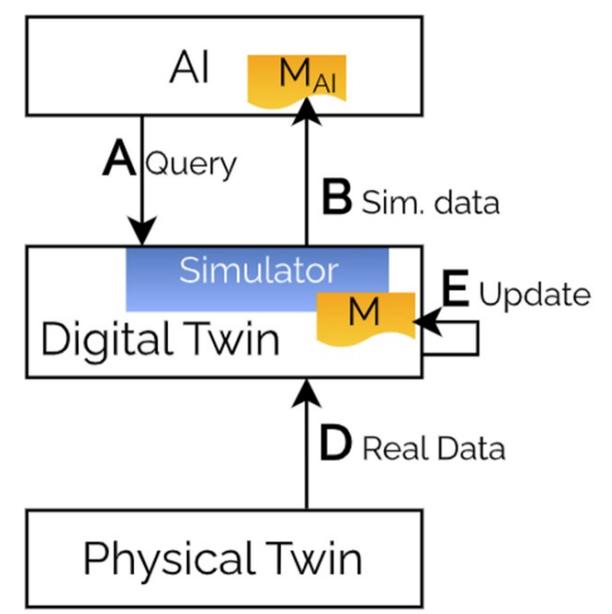
Domains/problems

Digital twins

AI/ML

Lifecycle models

Challenges/limitations

(a) Experimentable DT

(b) Experimentable DS

(c) Experimentable Model

(d) Policy DT

McMaster University

40

Deep learning proliferates
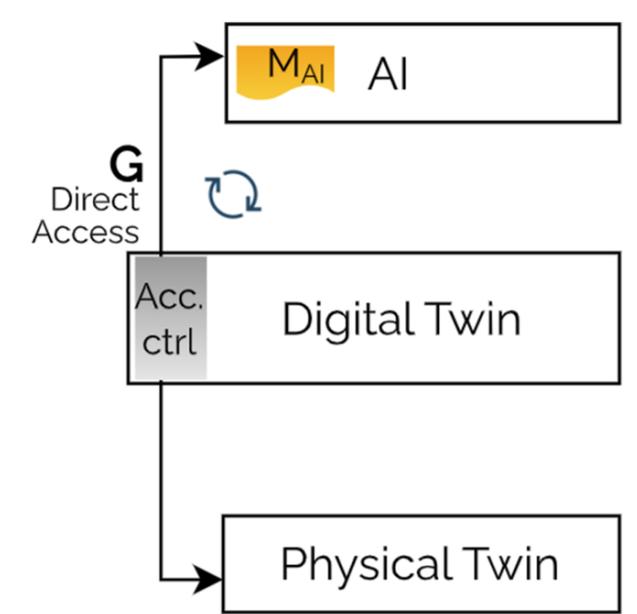
Domains/problems

Digital twins

AI/ML

Lifecycle models

Challenges/limitations

Table 7: AI methods

AI	#Studies	Studies
RL	18 (81.8%)	
↳ DRL	13 (59.1%)	
↳ Value	8 (36.4%)	[2, 10, 14, 15, 18, 19, 21, 22]
↳ Policy	5 (22.7%)	[6, 8, 9, 11, 13]
↳ Vanilla	5 (22.7%)	[4, 7, 16, 17, 20]
DL	4 (18.2%)	[1, 3, 5, 12]
TL	1 (4.5%)	[16]

McMaster University

41

Deep learning proliferates

Domains/problems

Digital twins

AI/ML

Lifecycle models

Challenges/limitations
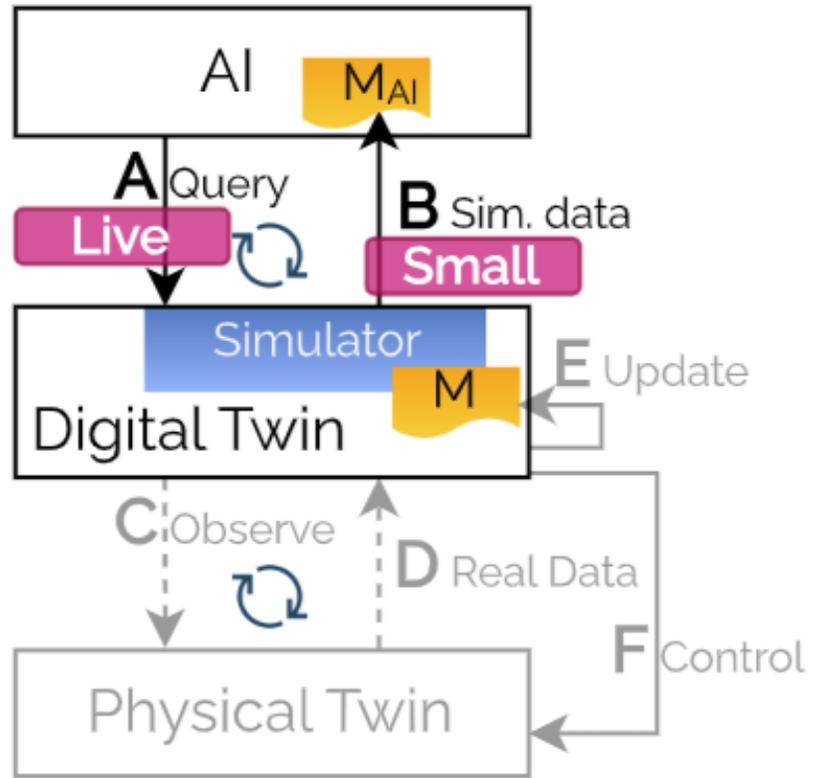
(a) Reinforcement Learning

(b) Deep Learning

McMaster University

42
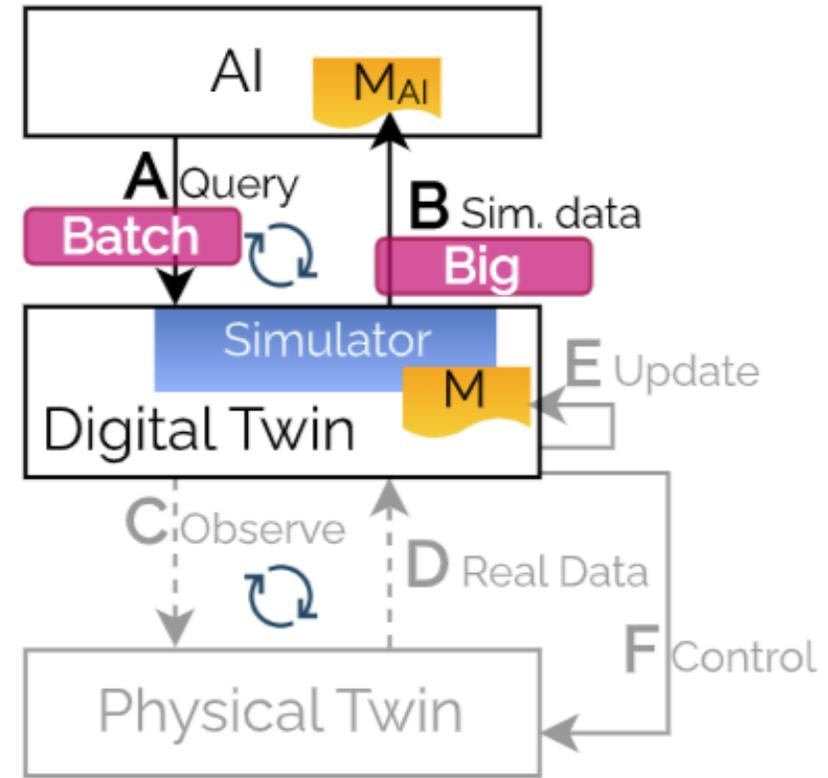
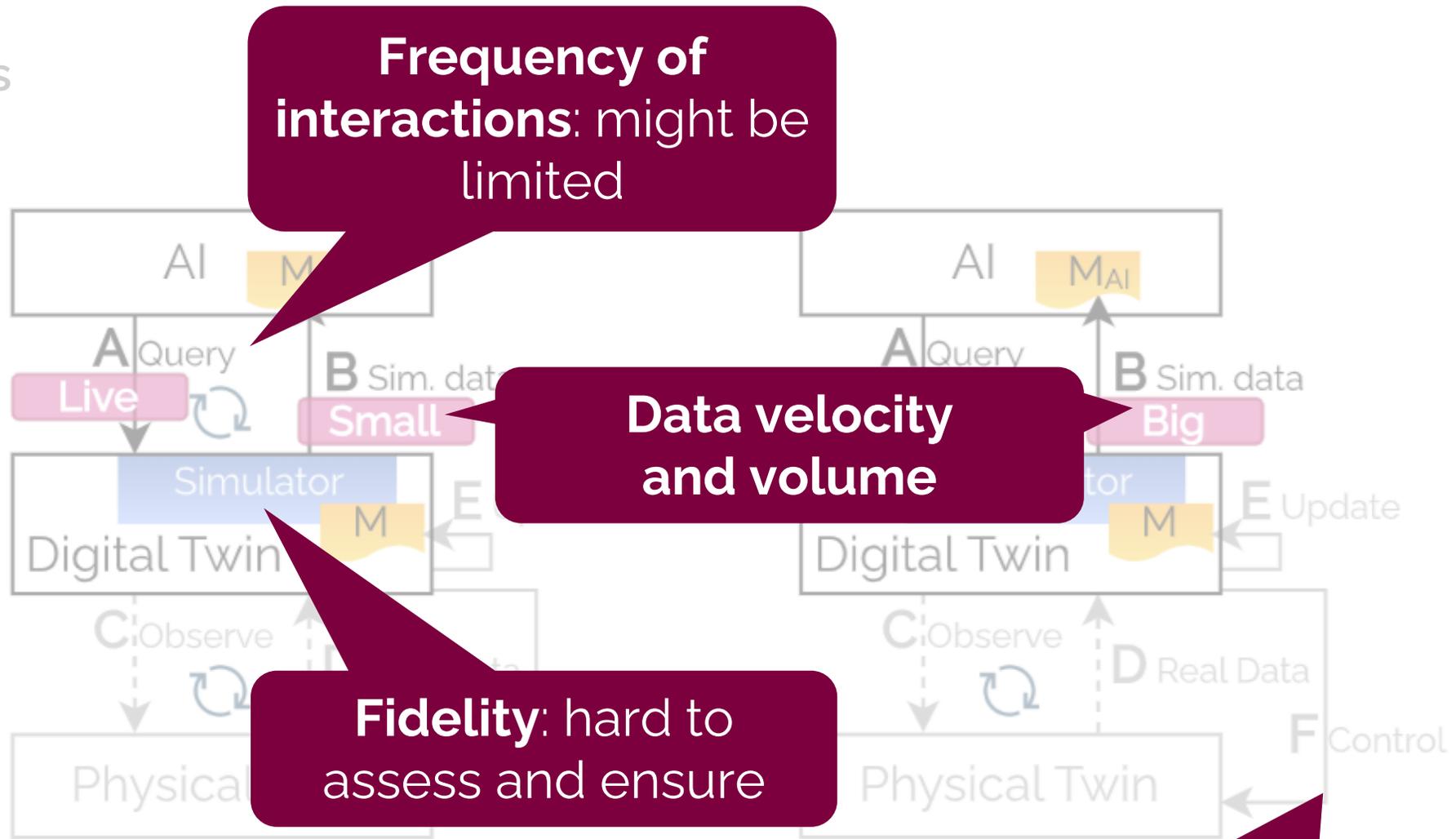(a) Reinforcement Learning

Domains/problems

Digital twins

AI/ML

Lifecycle models

Challenges/limitations

Frequency of interactions: might be limited

Data velocity and volume

Fidelity: hard to assess and ensure

Instrumentation

McMaster University

43

Digital twins and sustainability

Problem: our systems and methods are not sustainable

Sustainability

Technical | Economic | Environmental | Social

Systems Engineering

> " *meeting the needs of the present without compromising the ability of future generations to meet their own needs* (Brundtland)

> " *Technical sustainability addresses the **long-term use** of software-intensive systems and their appropriate **evolution** in a constantly changing execution environment*

P. Lago, S. A. Koçak, I. Crnkovic, and B. Penzenstadler. *Framing Sustainability as a Property of Software Quality*, Commun. ACM, vol. 58, no. 10, pp. 70–78, Sep. 2015.
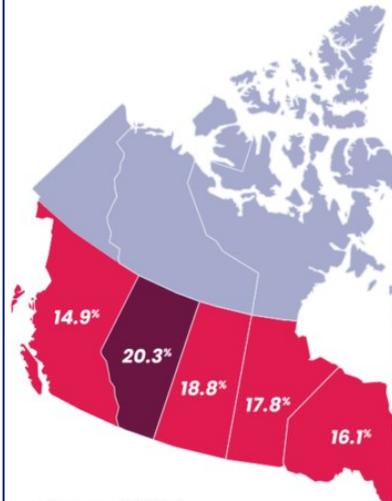
Amazon rainforest now emitting more CO2 than it absorbs

Cutting emissions more urgent than ever, say scientists, with forest producing more than a billion tonnes of carbon dioxide a year

Prevalence of Household Food Insecurity by Province, 2021

14.9%
20.3%
18.8%
17.8%
16.1%

Data Source: Statistics Canada, Canadian Income Survey (CIS) 2020. Data on the territories from this survey not available yet.

NATURE AND ENVIRONMENT | EUROPE

Air pollution: Nearly everyone in Europe breathing bad air

Rodrigo Menegat Schuinski
09/07/2023

With the EU voting on new air quality rules, satellite data shows **98%** eople face pollution above limits recommended by the World Health Organization.
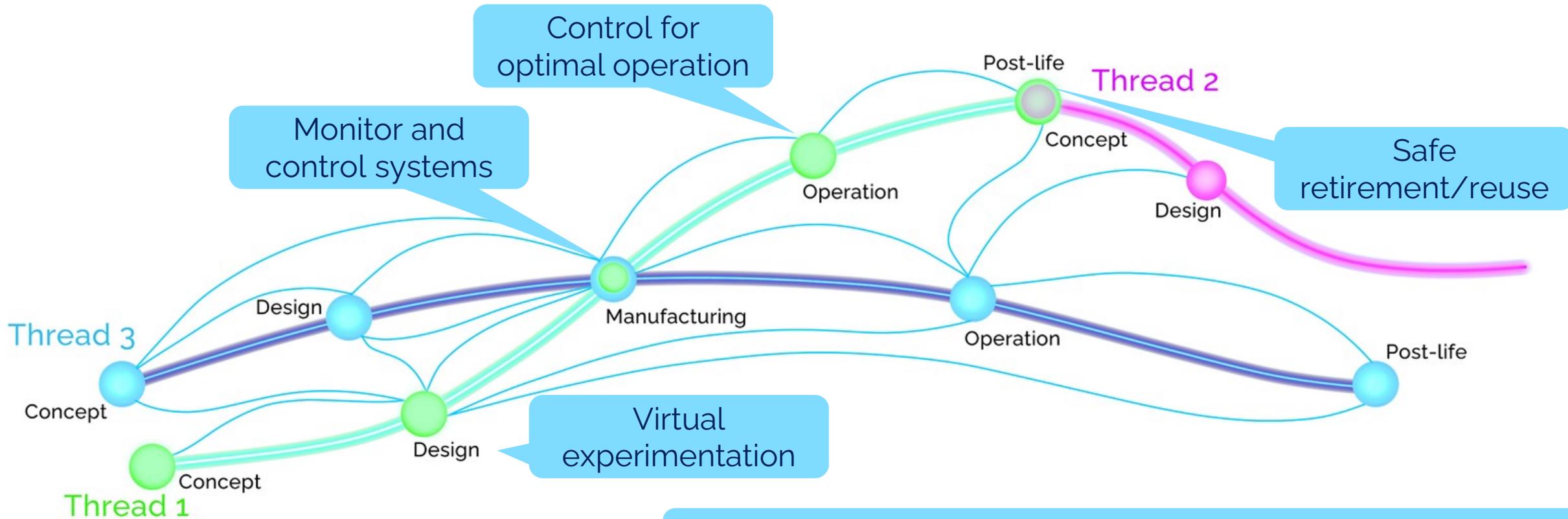
Digital Twins for Sustainable Systems

60% of organizations believe Digital Twin technology is critical to improving sustainability efforts.

(CapGemini, 2022)

Digital thread ► Digital fabric
I. David, D. Bork, and G. Kappel. "Circular Systems Engineering". In: Software and Systems Modeling (2023)

Top Strategic Technology Trends 2024
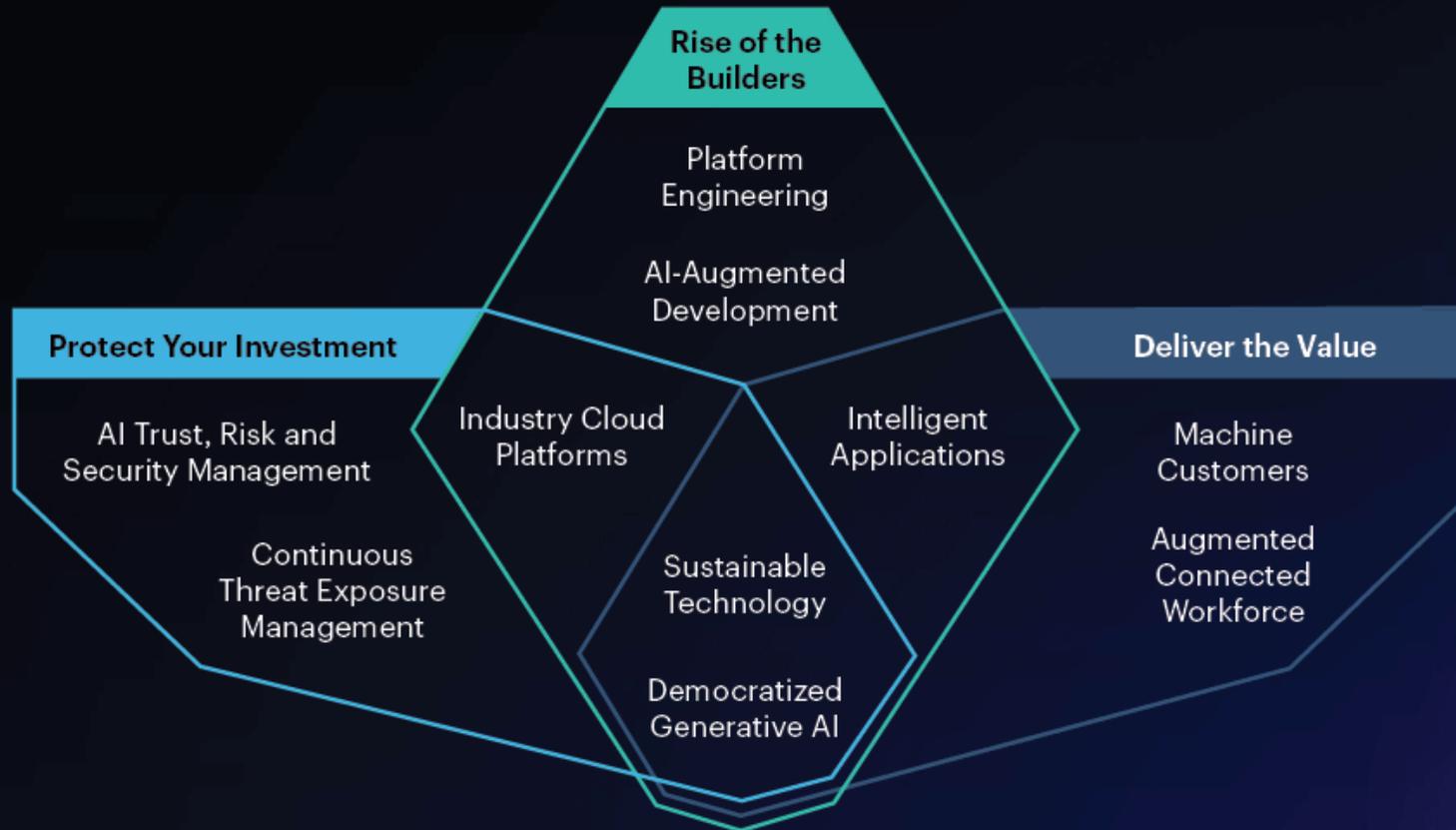
Rise of the Builders

Platform Engineering

AI-Augmented Development

Protect Your Investment

AI Trust, Risk and Security Management

Continuous Threat Exposure Management

Industry Cloud Platforms

Intelligent Applications

Sustainable Technology

Democratized Generative AI

Deliver the Value

Machine Customers

Augmented Connected Workforce

Gartner®

Top Strategic Technology Trends 2024

Rise of the Builders

By 2027, 80% of CIOs will have performance metrics tied to the sustainability of the IT organization.
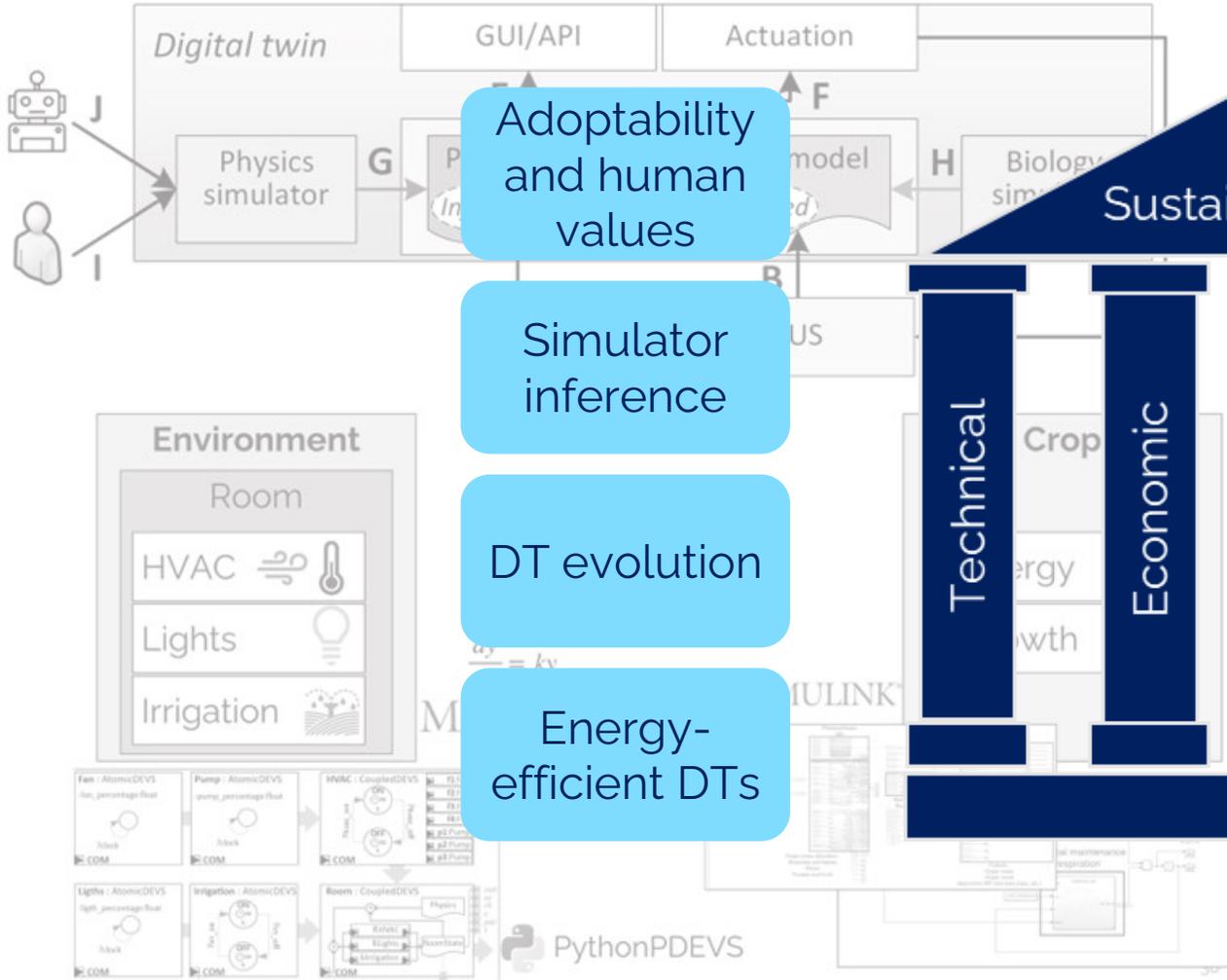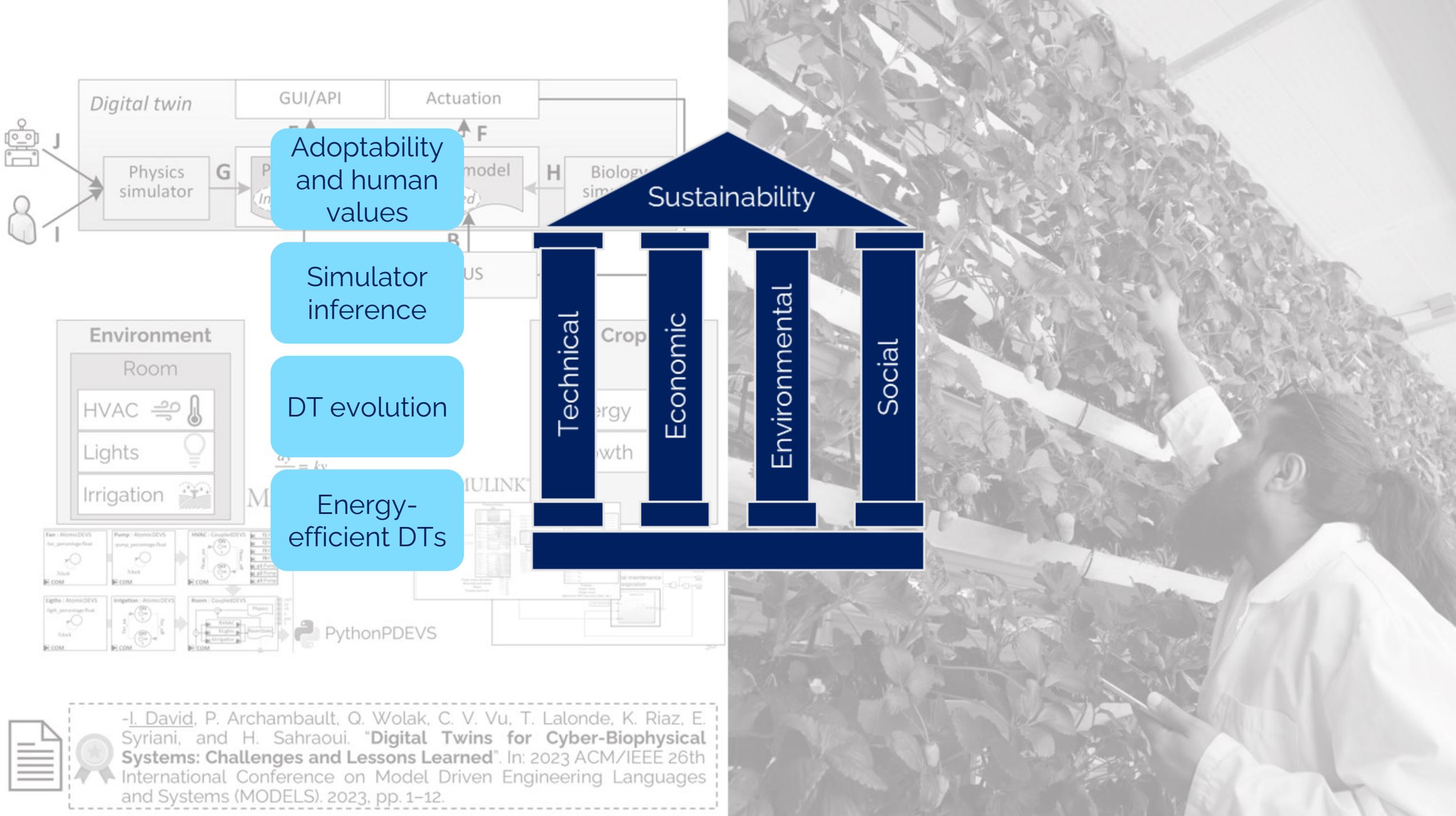
Source: Gartner

Threat Exposure
Management

Technology

Democratized
Generative AI

Workforce

Gartner

Adoptability and human values

Simulator inference

DT evolution

Energy-efficient DTs

Sustainability

Technical

Economic

Environmental

Social
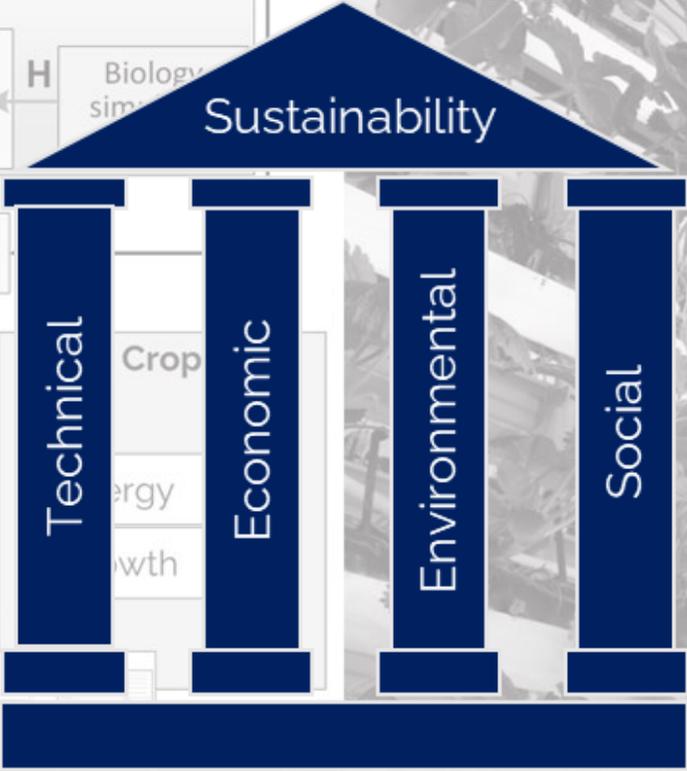
-I. David, P. Archambault, Q. Wolak, C. V. Vu, T. Lalonde, K. Riaz, E. Syriani, and H. Sahraoui. "Digital Twins for Cyber-Biophysical Systems: Challenges and Lessons Learned". In: 2023 ACM/IEEE 26th International Conference on Model Driven Engineering Languages and Systems (MODELS). 2023, pp. 1–12.

Energy-efficiency of Digital Twins

Simulator
Model

Digital Twin

data

control

Physical Twin

Precision

Pareto front

-Energy

PDE

Bond graph (a-causal)

KTG

DAE non-causal set

System dynamics

Bond graph (causal)

DAE causal set

Transfer function

DAE causal sequence

scheduling-hybrid DAE

DESS

Difference Equations

DEVS

Cellular Automata

Statecharts

Petri Nets

Process Interaction Discrete Event

Activity Scanning Discrete Event

3-Phase Approach Discrete Event

Timed Automata

Event Scheduling Discrete Event

State trajectory (observation frame)

Does not trivially translate to energy savings!

More abstract approximations

| State actions		
Add DEVS state	$addState(M, s) : M' = M \mid S \cup \{s\},\ ta(s) = \inf$	(8)
Remove DEVS state	$removeState(M, s) : M' = M \mid S \setminus \{s\}$	(9)
State transition actions		
Add internal transition	$addIntTransition(M, \delta = (s_i, s_j)) : M' = M \mid \Delta_{int} \cup \{\delta\}$	(10)
Remove internal transition	$removeIntTransition(M, \delta \in \Delta_{int}) : M' = M \mid \Delta_{int} \setminus \{\delta\}$	(11)
Add external transition	$addExtTransition(M, \delta = (s_i, s_j)) : M' = M \mid \Delta_{ext} \cup \{\delta\}$	(12)
Remove external transition	$removeExtTransition(M, \delta \in \Delta_{ext}) : M' = M \mid \Delta_{int} \setminus \{\delta\}$	(13)
Time advance actions		
Set time advance	$updateTa(M, s, t' \in \mathbb{R}_{0,+\infty}^{+}) : M' = M \mid ta(s) = t'$	(14)
Interacting with other models		
Add output	$addOutput(M, y) : M' = M \mid Y \cup \{y\}$	(15)
Remove output	$removeOutput(M, y \in Y) : M' = M \mid Y \setminus \{y\}$	(16)
Add input	$addInput(M, x) : M' = M \mid X \cup \{x\}$	(17)
Remove input	$removeInput(M, x \in X) : M' = M \mid X \setminus \{x\}$	(18)
Model initialization		
Set initial state	$setInitial(M, s \in S, 0 \le e \le ta(s)) : M' = M \mid q_{init} = (s, e)$	(19)

**A Survey of Techniques for Approximate Computing**

SPARSH MITTAL, Oak Ridge National Laboratory
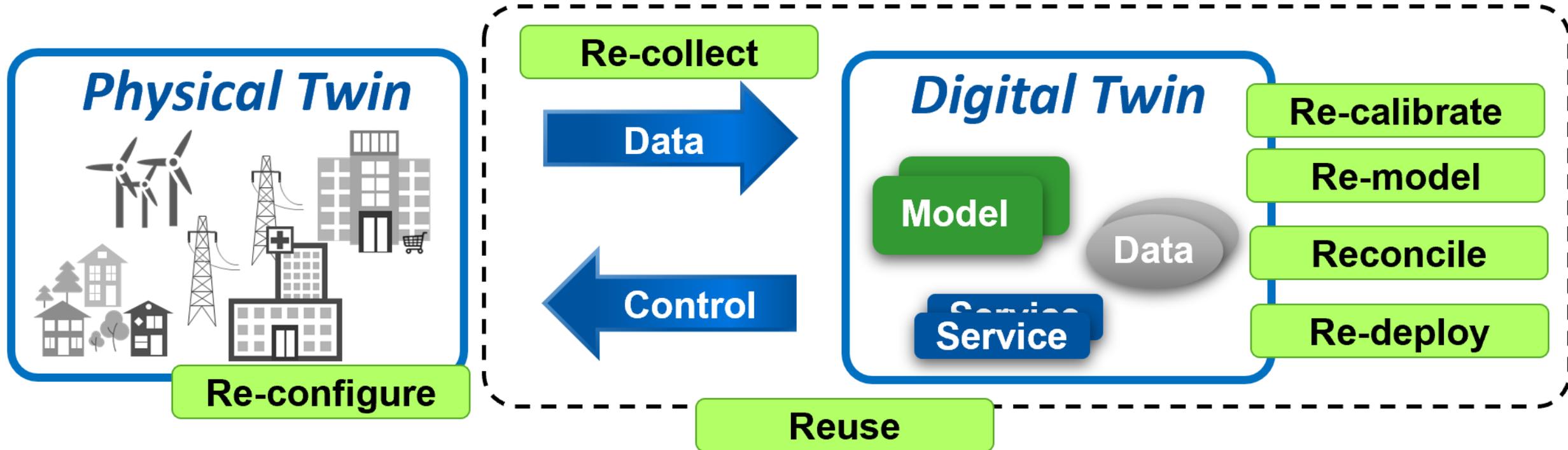
50

Evolution of Digital Twins

- Istvan David and Dominik Bork. "Towards a Taxonomy of Digital Twin Evolution for Technical Sustainability". In: MODELS-C 2023 Companion, Vasteras, Sweden. IEEE, 2023
- Judith Michael, Istvan David, and Dominik Bork. "Digital Twin Evolution for Sustainable Smart Ecosystems". In: MODELS-C 2024 Companion, Linz, Austria. ACM, 2024

Evolution of Digital Twins
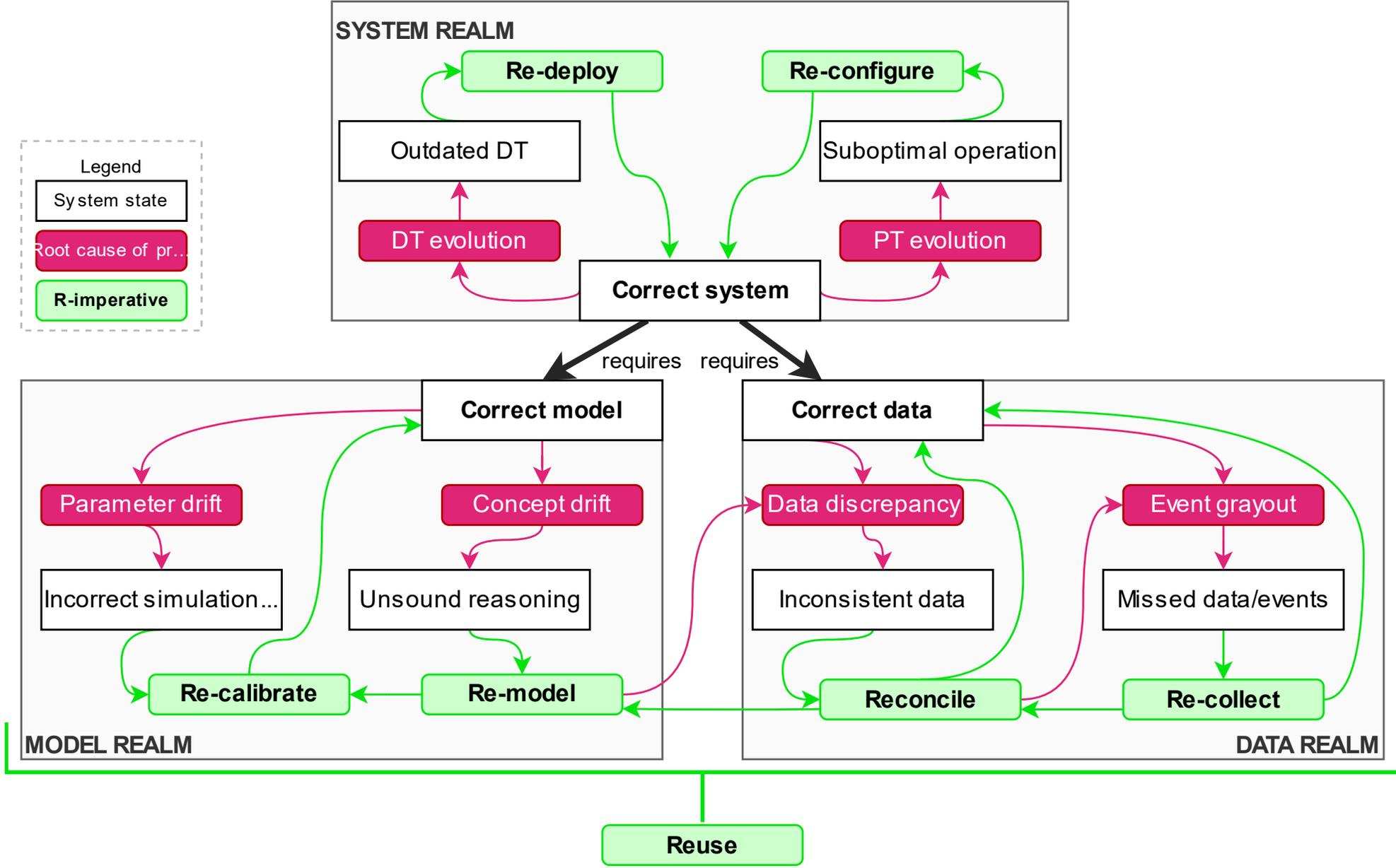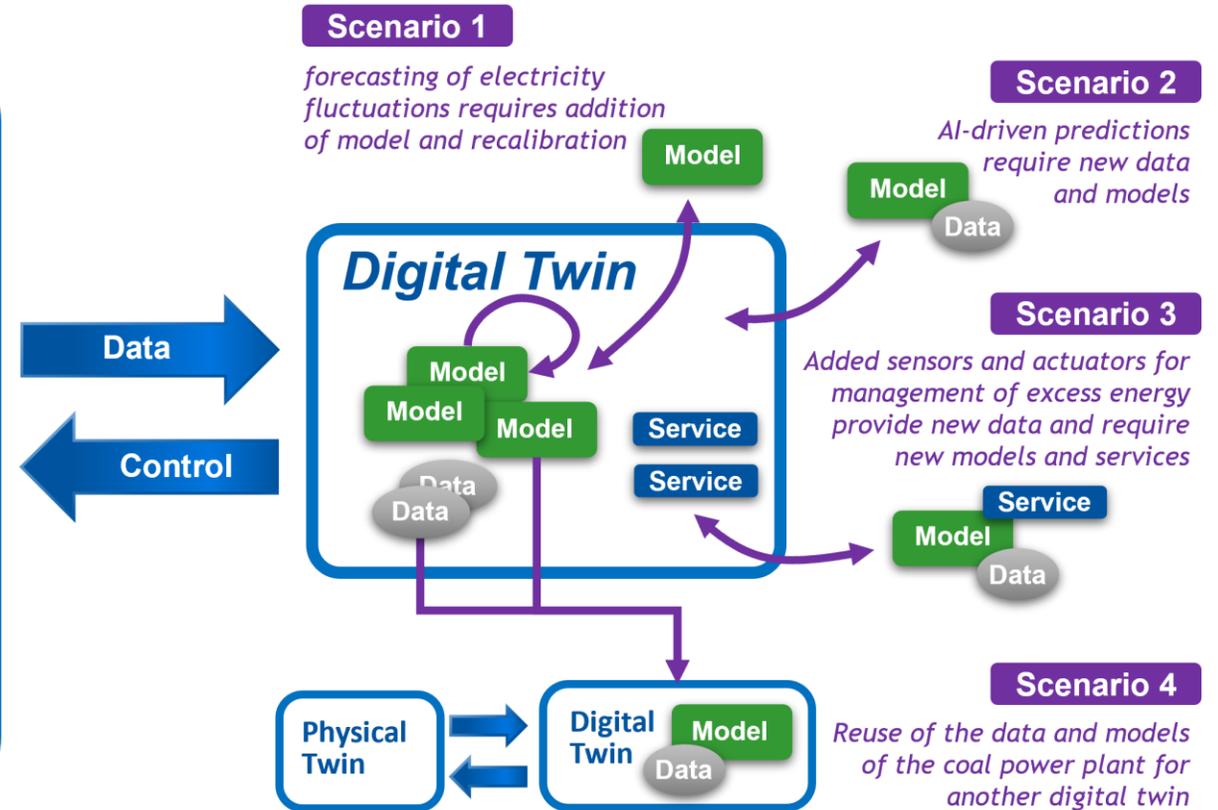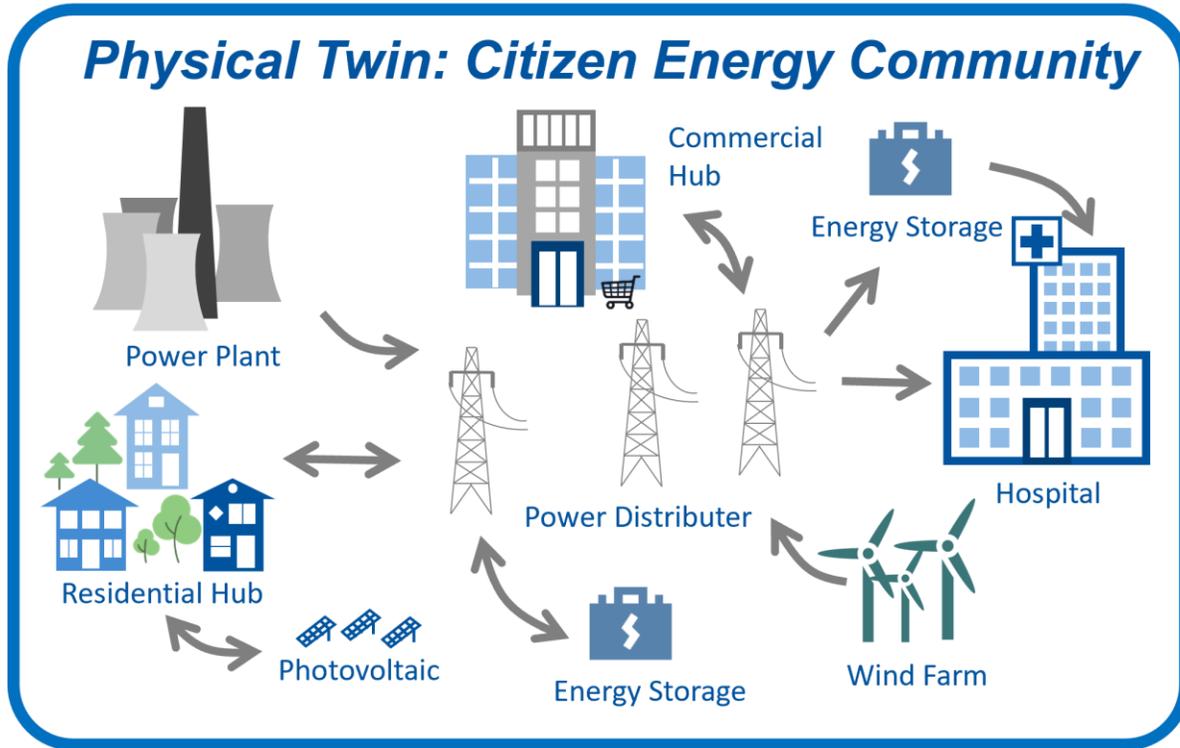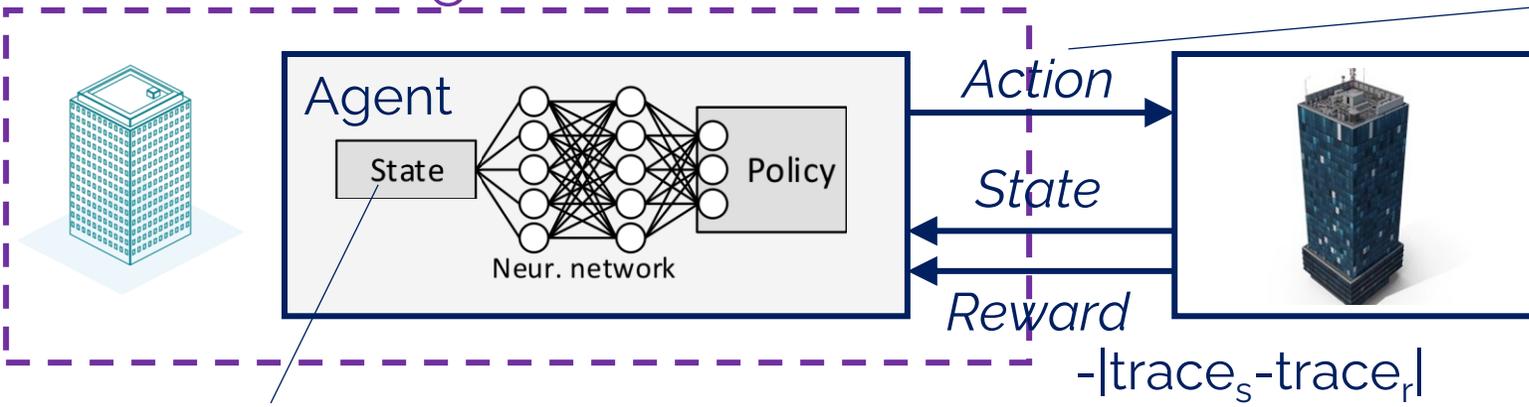
Evolution of Digital Twins

- Istvan David and Dominik Bork. "Towards a Taxonomy of Digital Twin Evolution for Technical Sustainability". In: MODELS-C 2023 Companion, Vasteras, Sweden. IEEE, 2023
- Judith Michael, Istvan David, and Dominik Bork. "Digital Twin Evolution for Sustainable Smart Ecosystems". In: MODELS-C 2024 Companion, Linz, Austria. ACM, 2024
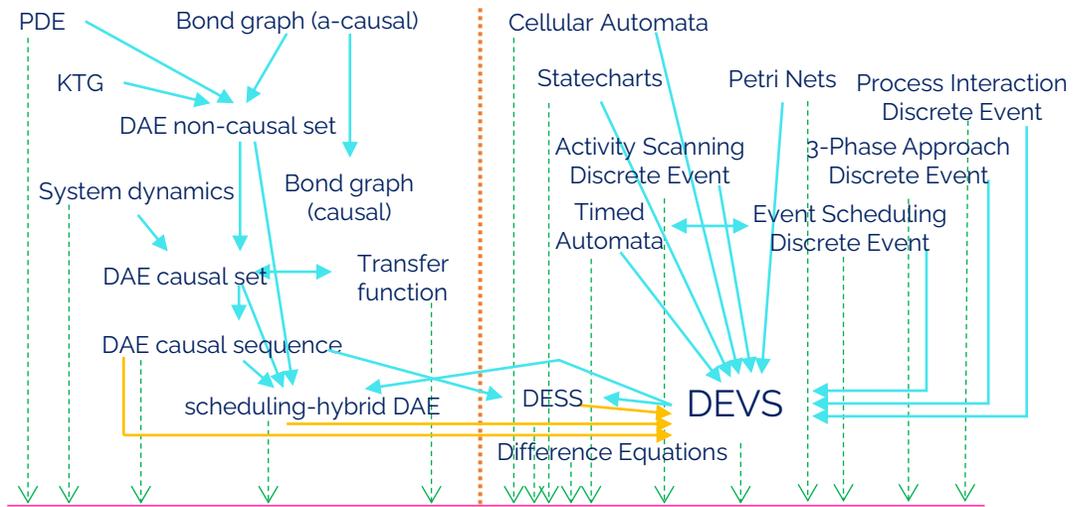
Rapid development of Digital Twins: Simulator inference by reinforcement learning

Digital Twin

Agent — State — Neur. network — Policy

a specific DEVS configuration (structure and parameters)

Action

State

Reward

$-|trace_s - trace_r|$

State actions		
Add DEVS state	$addState(M, s) : M' = M \mid S \cup \{s\},\ ta(s) = \inf$	(8)
Remove DEVS state	$removeState(M, s) : M' = M \mid S \setminus \{s\}$	(9)
State transition actions		
Add internal transition	$addIntTransition(M, \delta = (s_i, s_j)) : M' = M \mid \Delta_{int} \cup \{\delta\}$	(10)
Remove internal transition	$removeIntTransition(M, \delta \in \Delta_{int}) : M' = M \mid \Delta_{int} \setminus \{\delta\}$	(11)
Add external transition	$addExtTransition(M, \delta = (s_i, s_j)) : M' = M \mid \Delta_{ext} \cup \{\delta\}$	(12)
Remove external transition	$removeExtTransition(M, \delta \in \Delta_{ext}) : M' = M \mid \Delta_{int} \setminus \{\delta\}$	(13)
Time advance actions		
Set time advance	$updateTa(M, s, t' \in \mathbb{R}^+_{0,+\infty}) : M' = M \mid ta(s) = t'$	(14)
Interacting with other models		
Add output	$addOutput(M, y) : M' = M \mid Y \cup \{y\}$	(15)
Remove output	$removeOutput(M, y \in Y) : M' = M \mid Y \setminus \{y\}$	(16)
Add input	$addInput(M, x) : M' = M \mid X \cup \{x\}$	(17)
Remove input	$removeInput(M, x \in X) : M' = M \mid X \setminus \{x\}$	(18)
Model initialization		
Set initial state	$setInitial(M, s \in S, 0 \le e \le ta(s)) : M' = M \mid q_{init} = (s, e)$	(19)

...

State trajectory (observation frame)

- Istvan David and Eugene Syriani. "Automated Inference of Simulators in Digital Twins". In: Handbook of Digital Twins. To appear. CRC Press, 2023. isbn: 978-1-032-54607-0
- Istvan David and Eugene Syriani. "DEVS Model Construction as a Reinforcement Learning Problem". In: 2022 Annual Modeling and Simulation Conference (ANNSIM). IEEE. 2022, pp. 30–41.
- Istvan David, Jessie Galasso, and Eugene Syriani. "Inference of Simulation Models in Digital Twins by Re-inforcement Learning". In: MODELS-C 2021, IEEE, pp. 221–224.

Social sustainability of Digital Twins

Individual

Whose decisions are twinned anyways?

- Inclusive partnerships are key in fostering societally sustainability
- Include those who may be affected by the Digital Twins that govern socio-technical systems

Society

Adoption in lower-income economies?

- Digital solutions that might not be viable in another context
- Variability, product families, validity frames

Organizations

Who will adopt these solutions?

- Higher-digitalized domains: lack of agility, lack of understanding of benefits
- Lower-digitalized domains: lack of expertise, lack of trust

VIENNA MANIFESTO ON DIGITAL HUMANISM

VIENNA, MAY 2019

»The system is failing« — stated by the founder of the Web, Tim Berners-Lee — emphasizes that while digitalization opens unprecedented opportunities, it also raises serious concerns: the monopolization of the Web, the rise of extremist opinions and behavior orchestrated by social media, the formation of filter bubbles and echo chambers as islands of disjoint truths, the loss of privacy, and the spread of digital surveillance. Digital technologies are disrupting societies and questioning our understanding of what it means to be human. The stakes are high and the challenge of building a just and democratic society with humans at the center of technological progress needs to be addressed with determination as well as scientific ingenuity. Technological innovation demands social innovation, and social innovation requires broad societal engagement.

This manifesto is a call to deliberate and to act on current and future technological development. We encourage our academic communities, as well as industrial leaders, politicians, policy makers, and professional societies all around the globe, to actively participate in policy formation. Our demands are the result of an emerging process that unites scientists and practitioners across fields and topics, brought together by concerns and hopes for the future. We are aware of our joint responsibility for the current situation and the future – both as professionals and citizens.

Today, we experience the co-evolution of technology and humankind. The flood of data, algorithms, and computational power is disrupting the very fabric of society by changing human interactions, societal institutions, economies, and political structures. Science and the humanities are not exempt. This disruption simultaneously creates and threatens jobs, produces and destroys wealth, and improves and damages our ecology. It shifts power structures, thereby blurring the human and the machine.

The quest is for enlightenment and humanism. The capability to automate human cognitive activities is a revolutionary aspect of computer science / informatics. For many tasks, machines surpass already what humans can accomplish in speed, precision, and even analytic deduction. The time is right to bring together humanistic ideals with critical thoughts about technological progress. We therefore link this manifesto to the intellectual tradition of humanism and similar movements striving for an enlightened humanity.

Like all technologies, digital technologies do not emerge from nowhere. They are shaped by implicit and explicit choices and thus incorporate a set of values, norms, economic interests, and assumptions about how the world around us is or should be. Many of these choices remain hidden in software programs implementing algorithms that remain invisible. In line with the renowned Vienna Circle and its contributions to modern thinking, we want to espouse critical rational reasoning and the interdisciplinarity needed to shape the future.

We must shape technologies in accordance with human values and needs, instead of allowing technologies to shape humans. Our task is not only to rein in the downsides of information and communication technologies, but to encourage human-centered innovation. We call for a Digital Humanism that describes, analyzes, and, most importantly, influences the complex interplay of technology and humankind, for a better society and life, fully respecting universal human rights.

McMaster University

Twin transition

Top Strategic Technology Trends 2024

Rise of the Builders

By 2027, 80% of CIOs will have performance metrics tied to the sustainability of the IT organization.
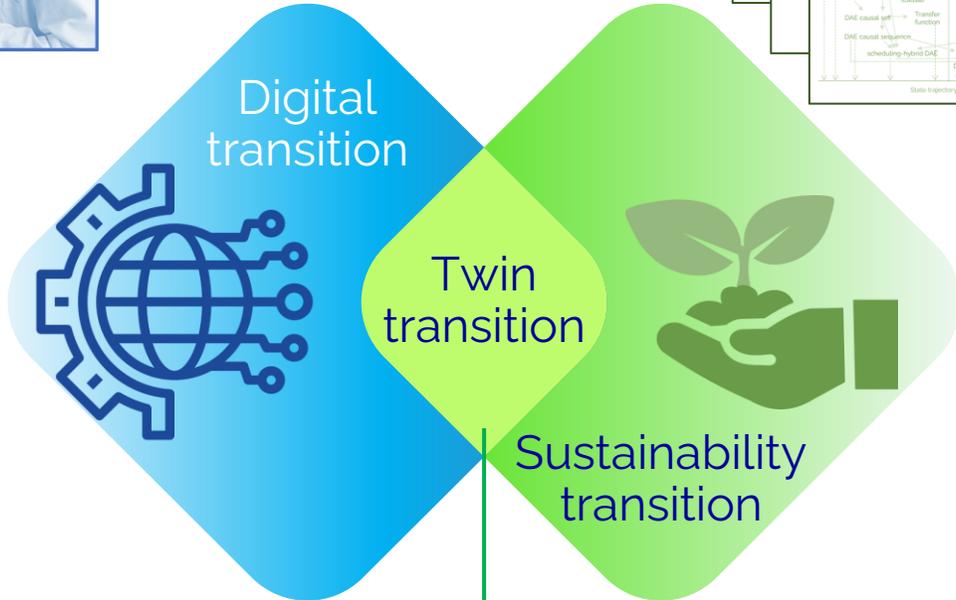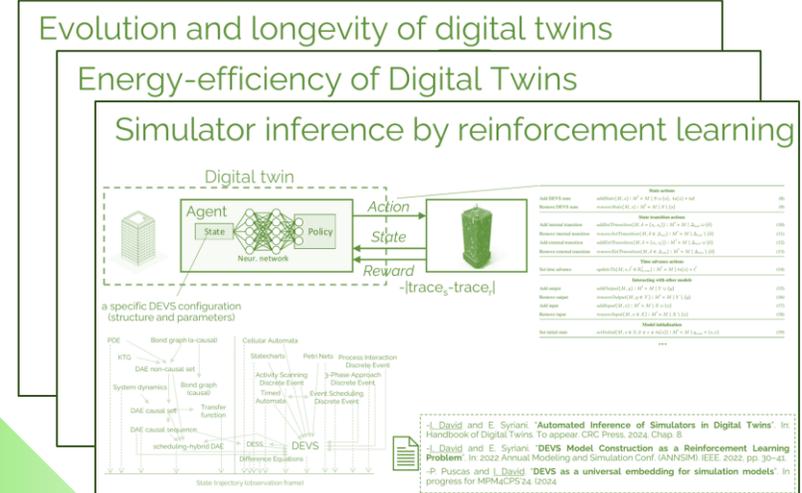
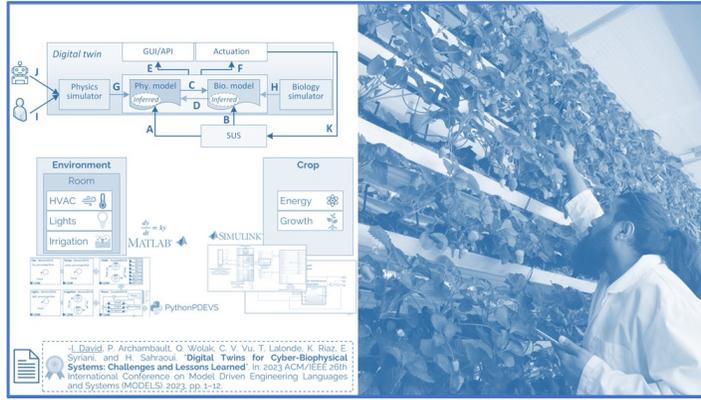Source: Gartner

Threat Exposure
Management

Technology

Democratized
Generative AI

Workforce

Gartner

Sustainable systems

...by sustainable methods

Evolution and longevity of digital twins

Energy-efficiency of Digital Twins

Simulator inference by reinforcement learning
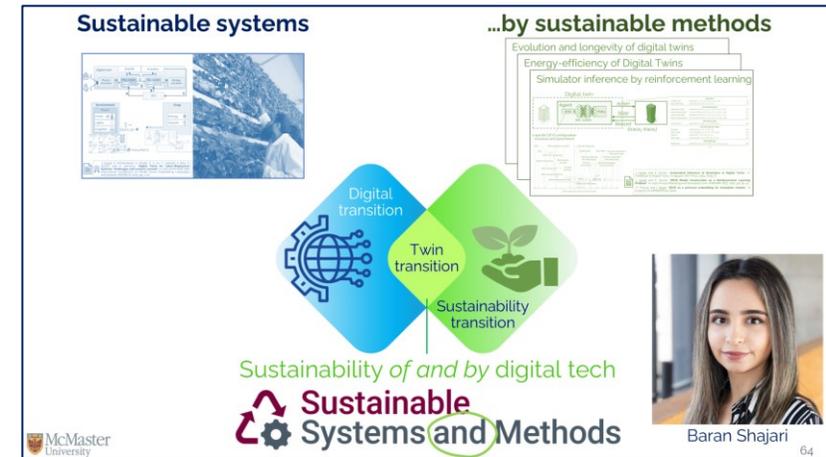

Digital transition

Twin transition

Sustainability transition

Sustainability *of and by* digital tech
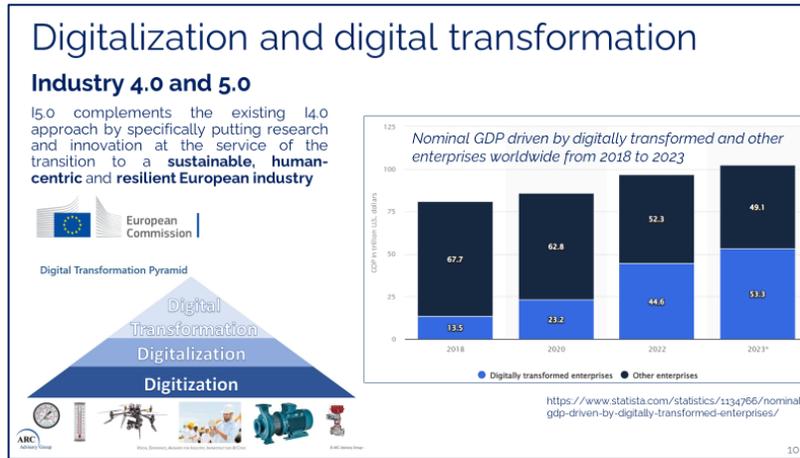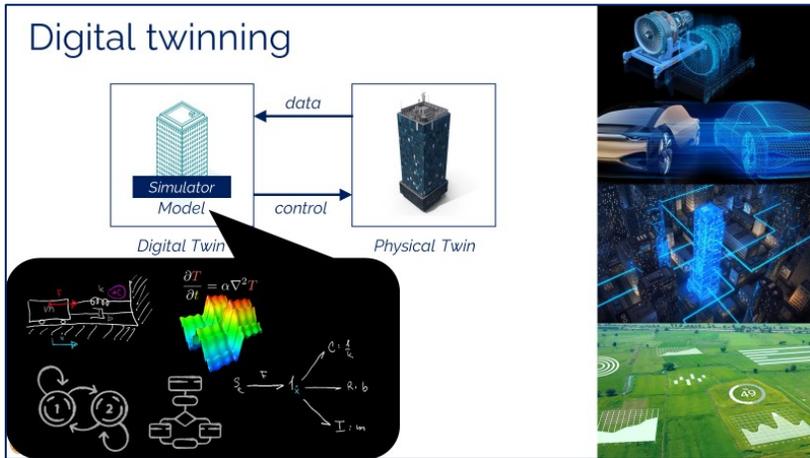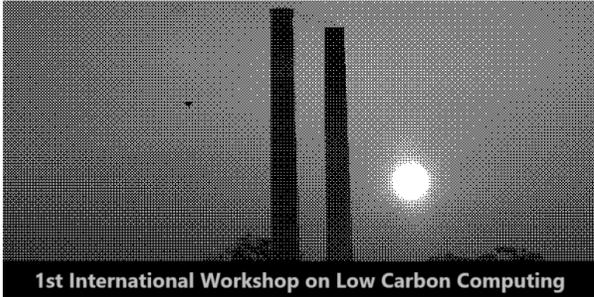
Sustainable Systems and Methods

Baran Shajari

By way of conclusion

Foundations and Applications of Digital Twins
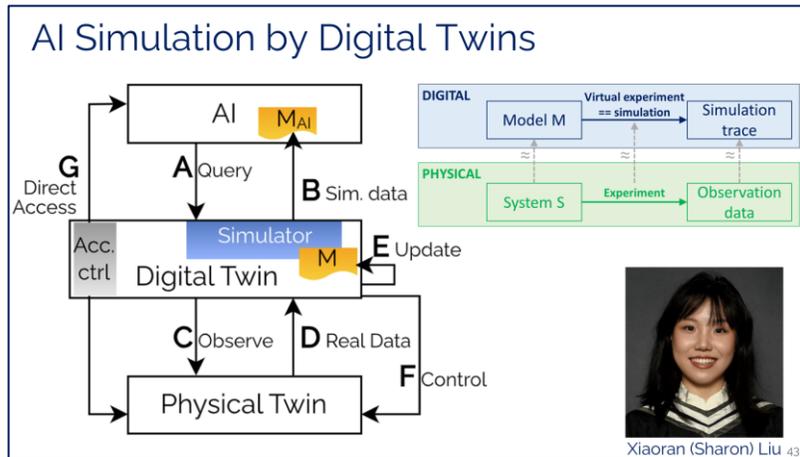
Upcoming events and deadlines

1st International Workshop on Low Carbon Computing

19th Conference on Research Challenges in Information Science (RCIS'25)
May 20–23, 2025
Seville, Spain

CAiSE'25
37th International Conference on Advanced Information Systems Engineering
Vienna, Austria · June 16-20, 2025
Theme: Bridging the Silos

EMMSAD

Book series

Simulation Foundations, Methods and Applications

Artificial Intelligence in Modeling&Simulation
PJ Giabbanelli, I. David. 2025. Springer.
Intent to submit a chapter: November '24. Intended publication: end of 2025.

Software and Systems Modeling

Theme Section: **Modeling for Simulation**
Intent to submit: 1 Jan, 2025
Submission deadline: 1 Apr, 2025

Theme Section: **Modeling and Sustainability**

Just wrapped up

Computer Networks
Impact Factor: 5.6   Cite Score: 10.7

Special Issue on
Digital Twins for Open, Programmable, and AI-driven Wireless Networks

Theme Section: **Digital Twins for Open, Programmable, and AI-driven Wireless Networks**
Submission deadline: **now**

McMaster University

62

BRIGHTER WORLD

McMaster University | ENGINEERING

Sustainable Systems and Methods

Visit or join us in Hamilton, Ontario!