Digital Twins: Foundations and Applications

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McMaster University

Toronto Metropolitan University

Sustainable Systems and Methods

Sustainable Systems and Methods

*Sustainable systems **by** sustainable methods*

Sustainability

- Sustainable systems engineering
- Energy-efficient simulators
- Environmental sustainability
- Green computing
- Human-in-the-loop
- System evolution

Digitalization

- Digital twins
- Digital thread
- Machine learning / AI
- Tool chains and process tools

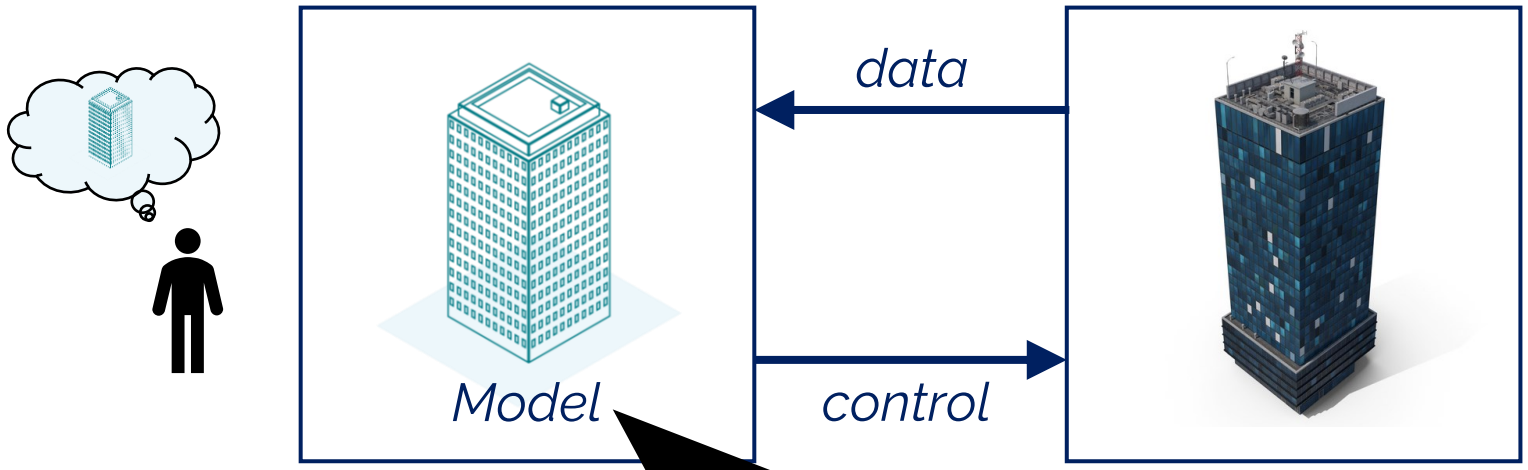
Modeling & Simulation

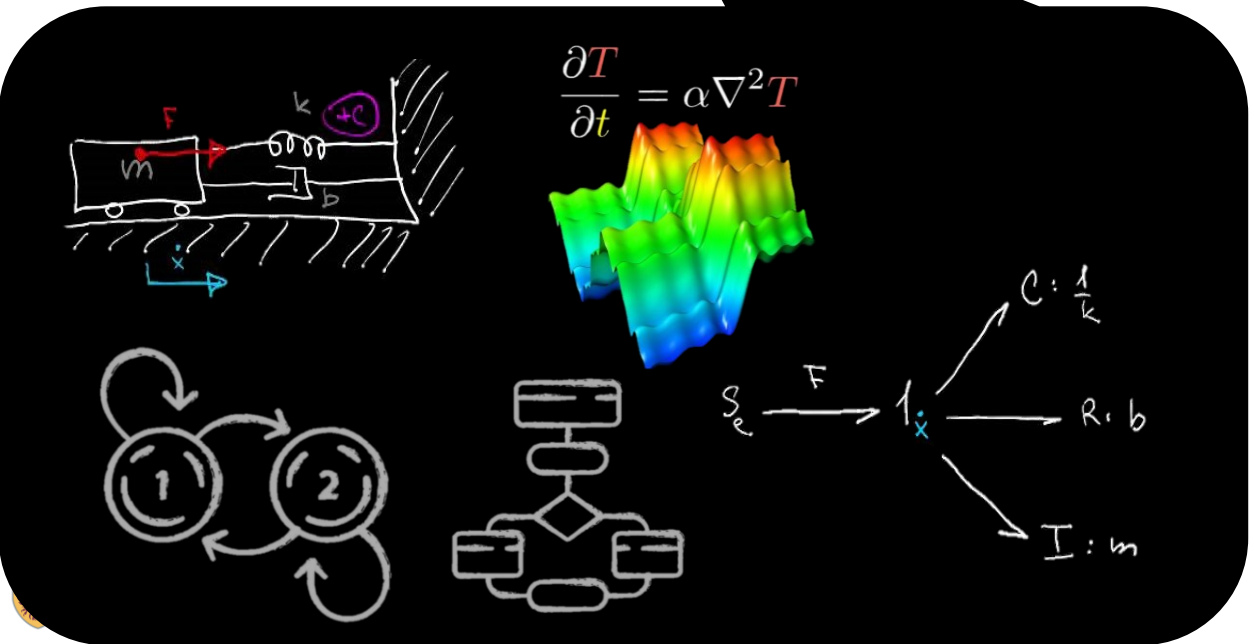
- Model-driven engineering (MDE)
- Model-based systems engineering (MBSE)
- Multi-paradigm modeling (MPM)
- Co-simulation
- Discrete event simulations

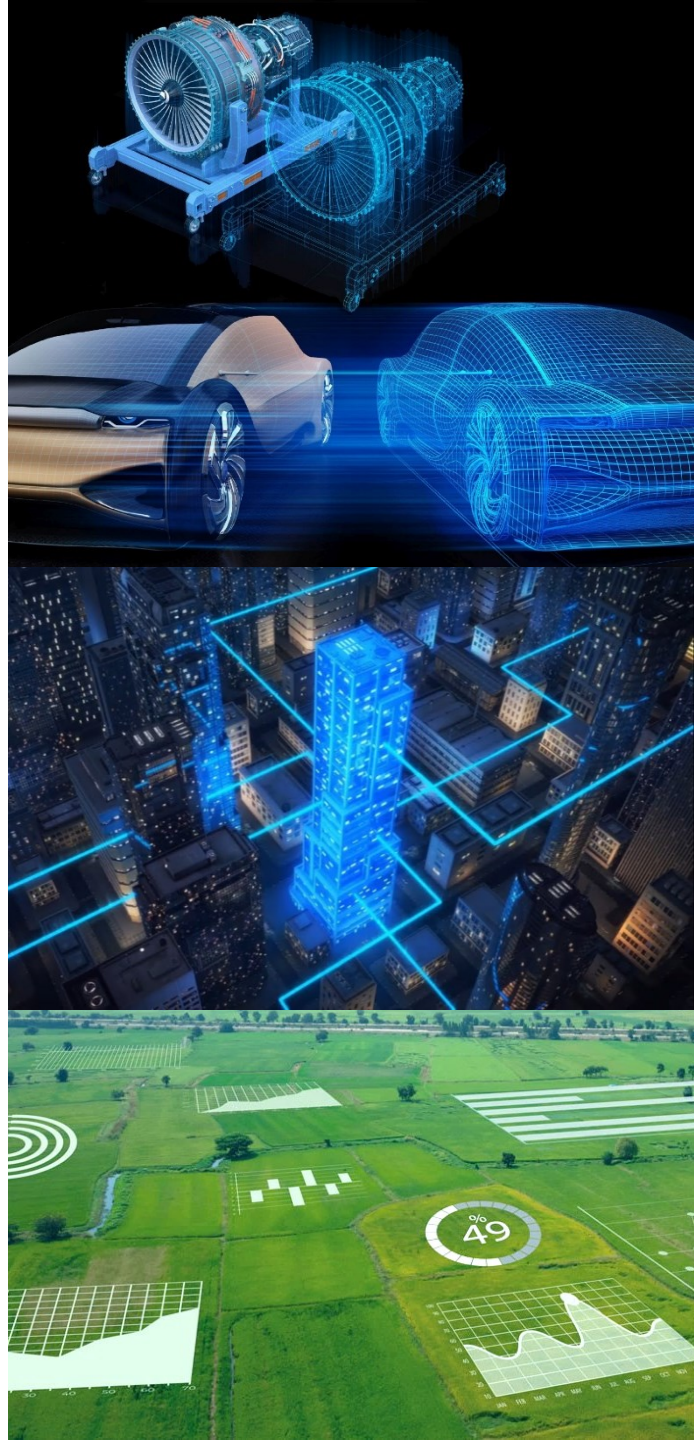
https://istvandavid.com/lab

Digital twins

Digital twinning

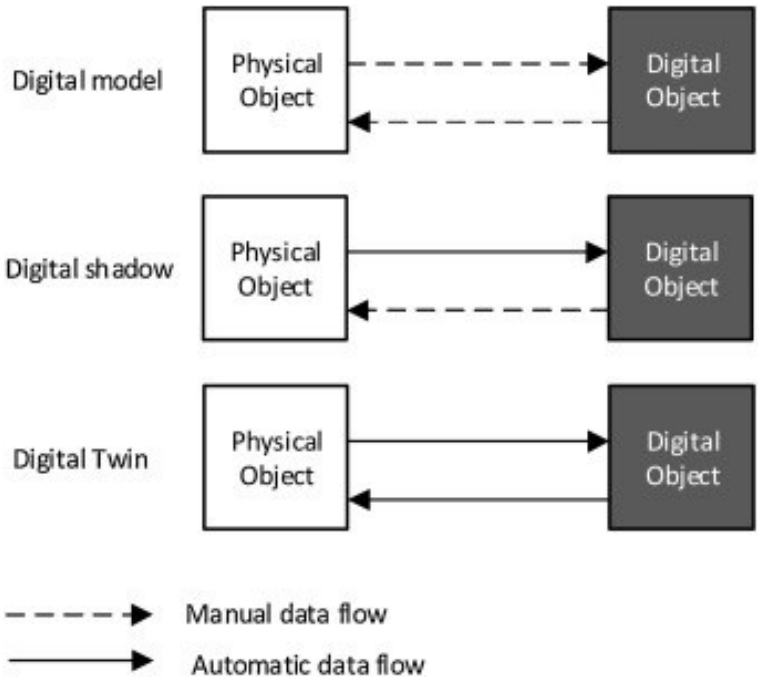




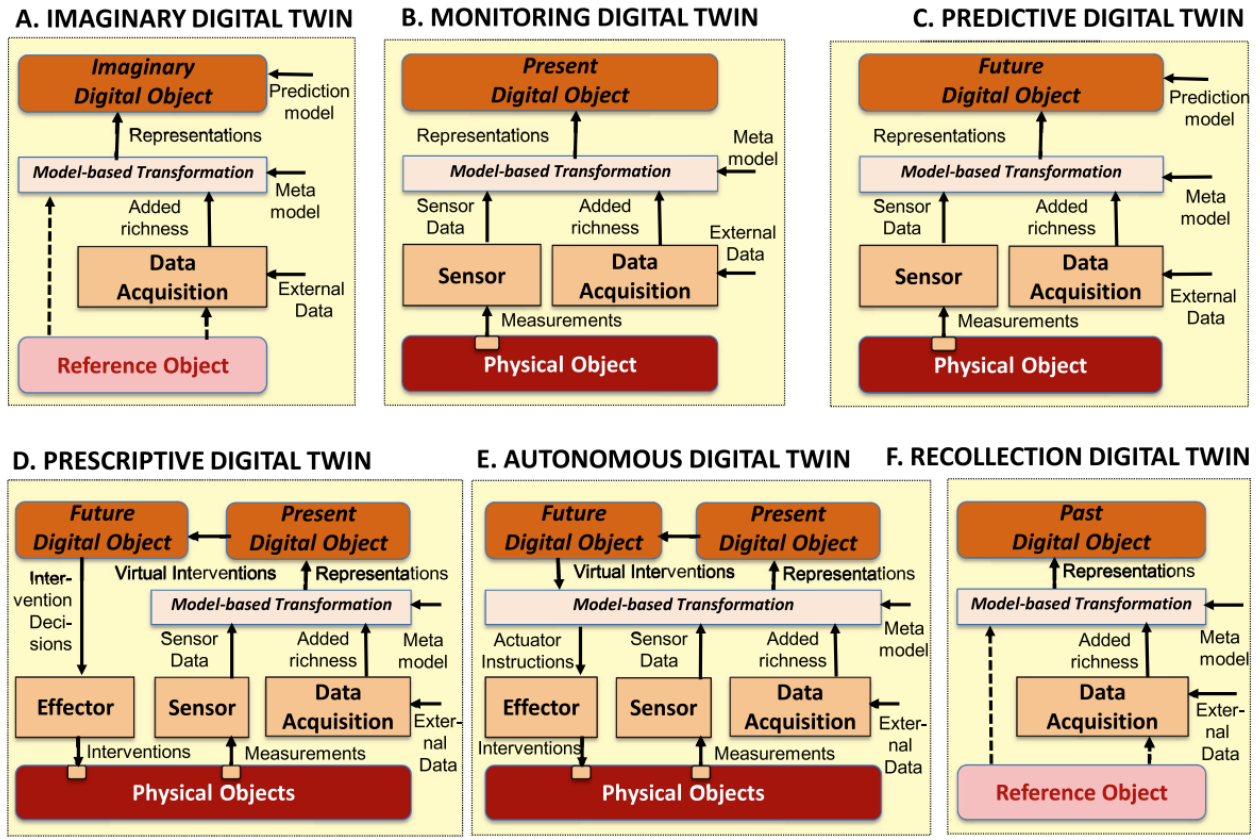


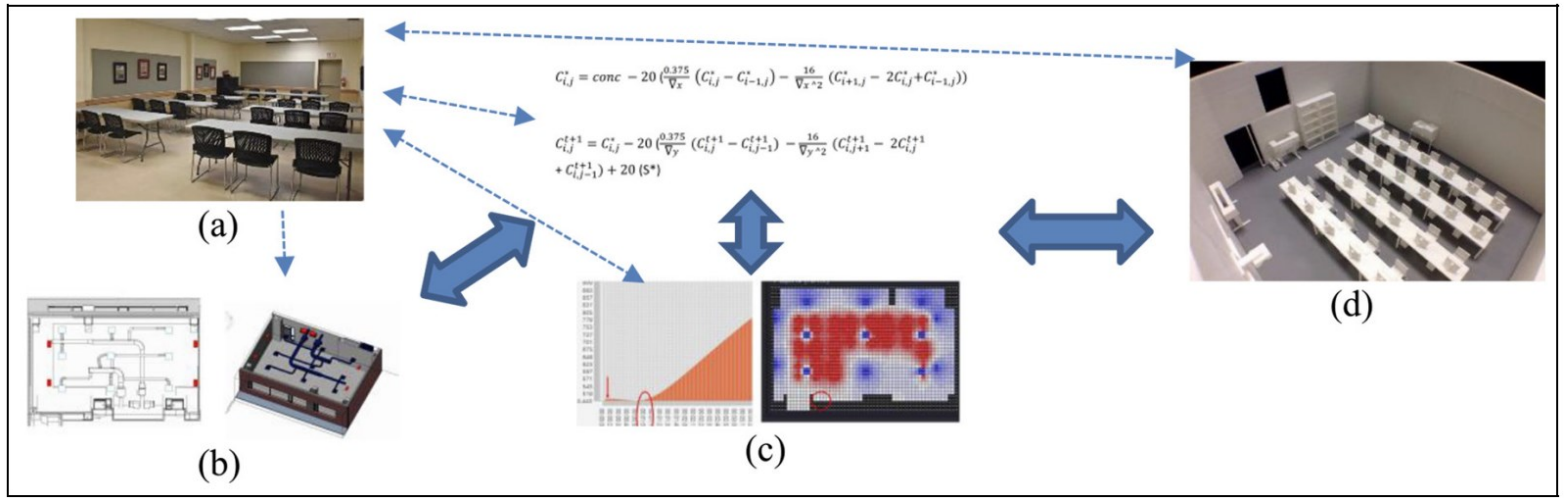
Digital "X"

Verdouw et al., 2021



Kritzinger et al., 2018





A DEVS-based engine for building digital quadruplets

Daniella Niyonkuru and Gabriel Wainer

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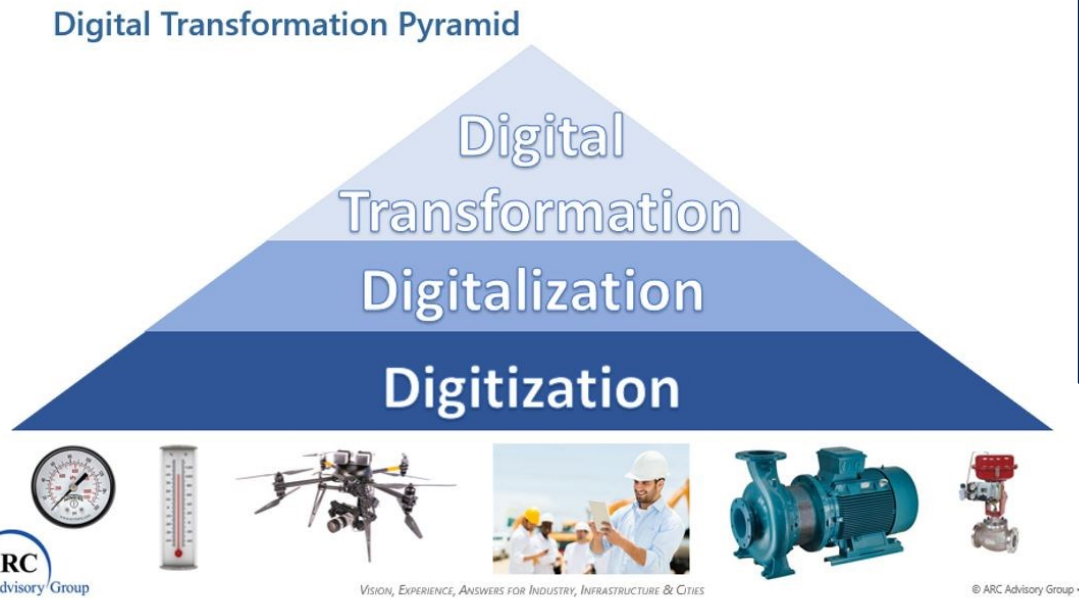
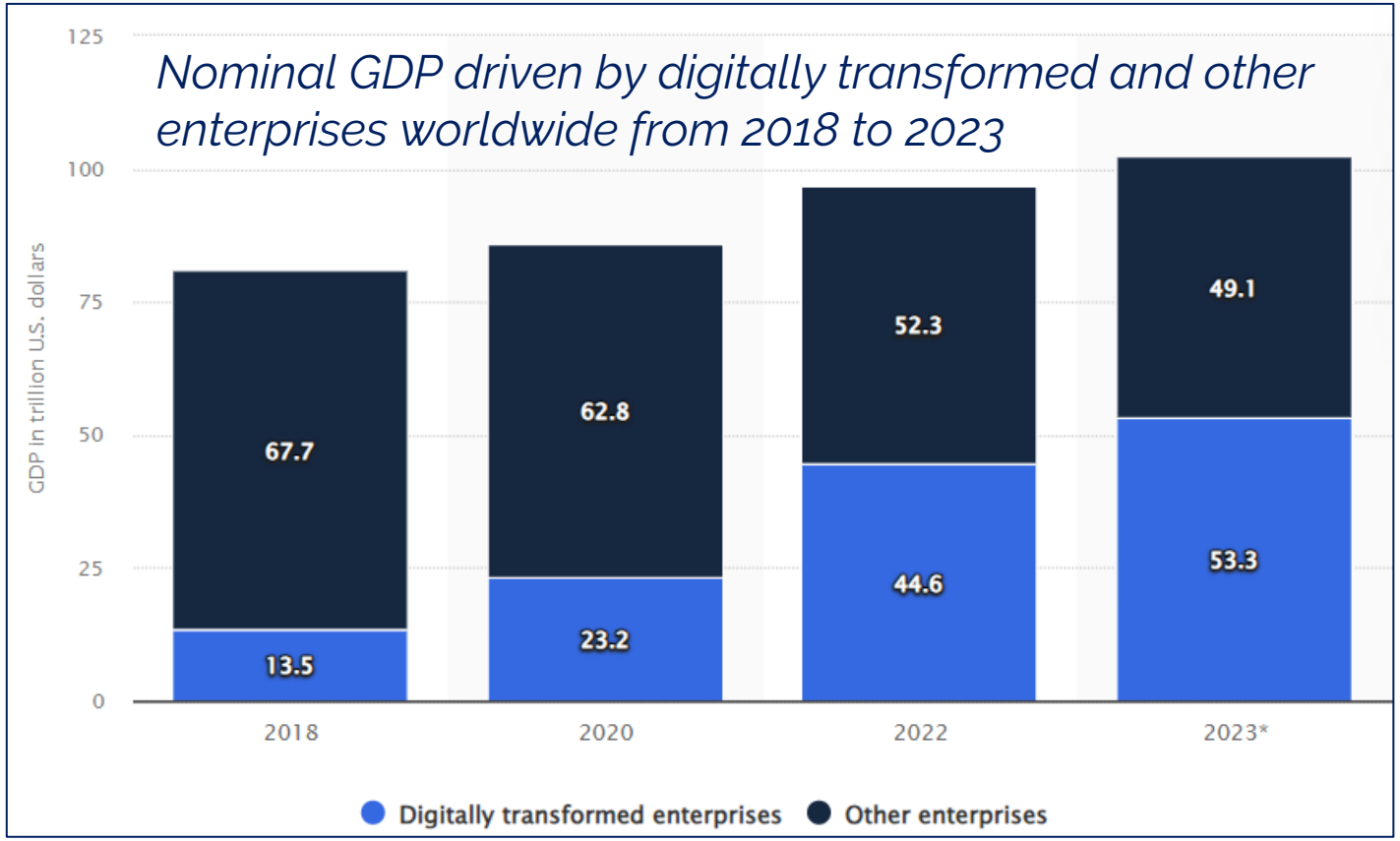
Digitalization and digital transformation

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

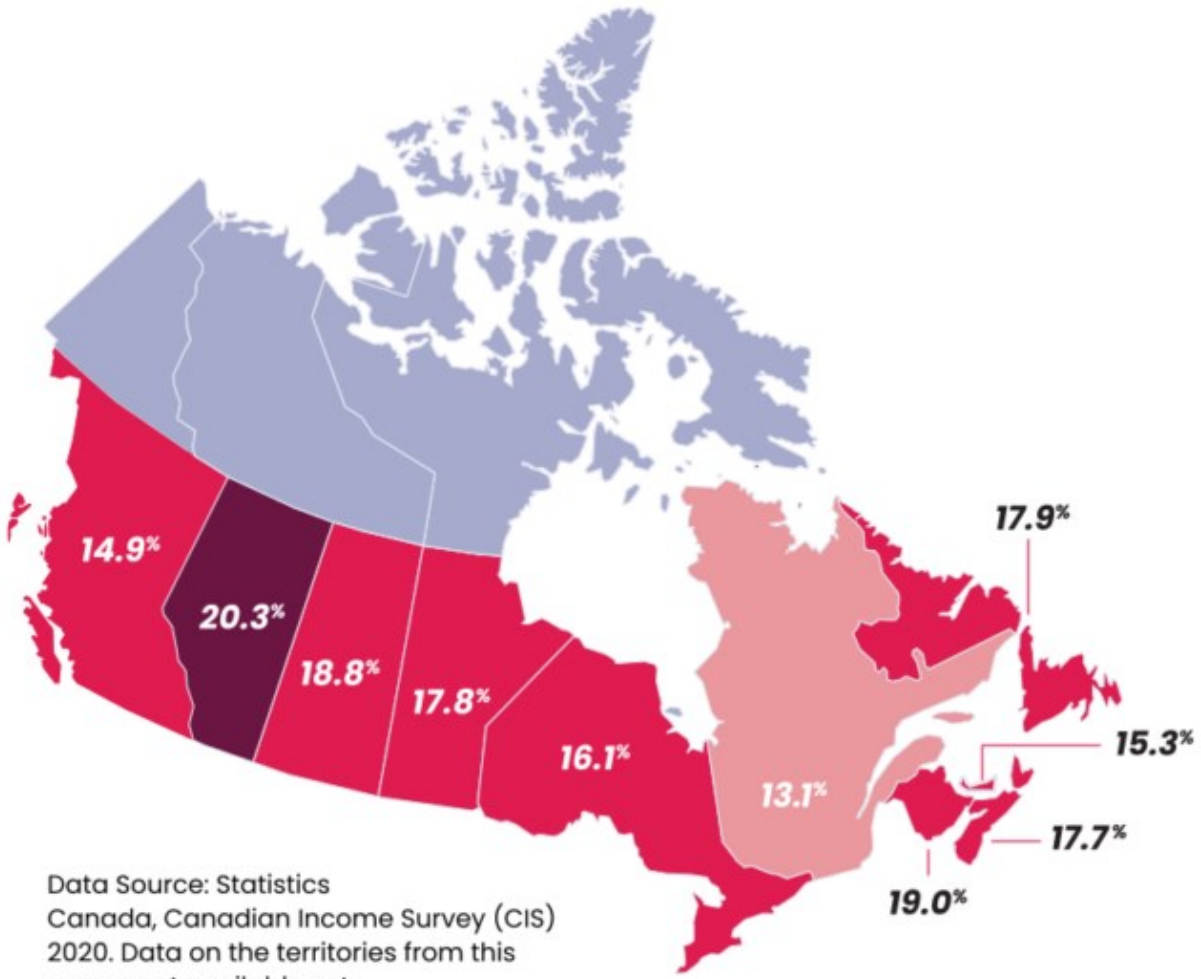




https://www.statista.com/statistics/1134766/nominal-gdp-driven-by-digitally-transformed-enterprises/

Digital twins for cyber-biophysical systems

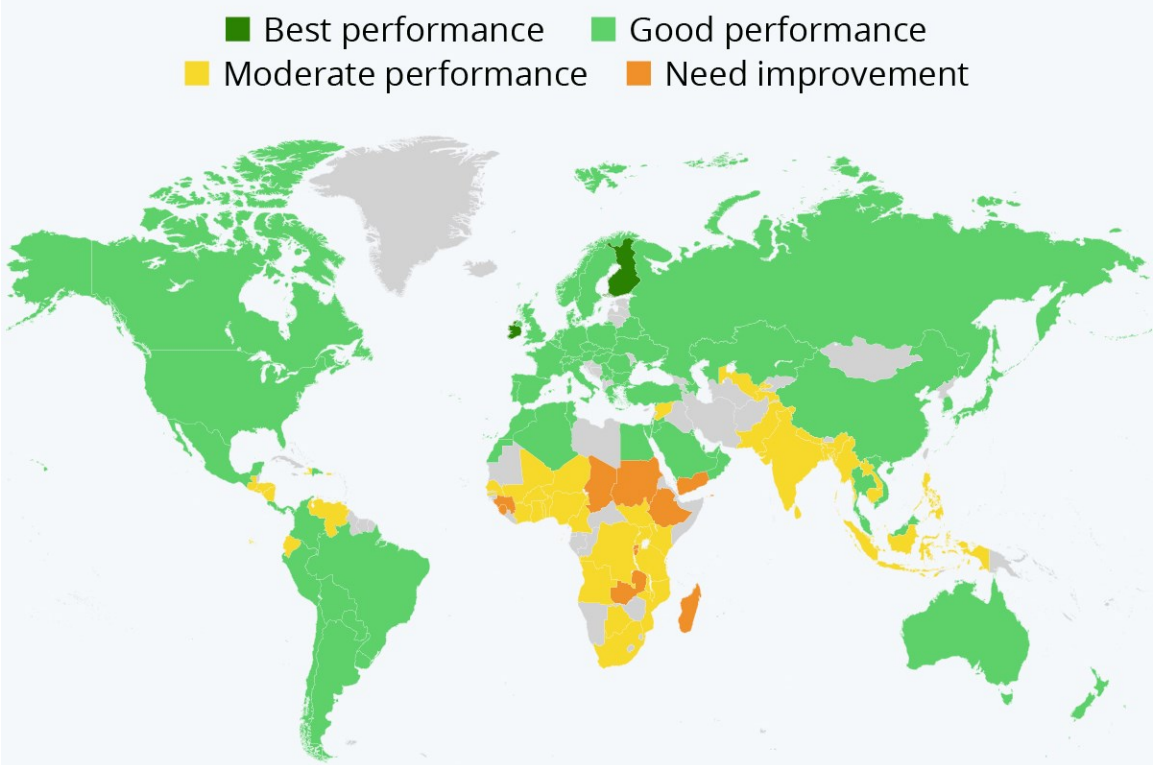
Prevalence of Household Food Insecurity by Province, 2021



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

The Global State of Food Security

Best and worst performing countries for food security in 2020*



* Affordability, availability, safety, quality and natural resources of food based on 59 unique indicators across 113 countries.

Source: Economist Intelligence Unit

statista

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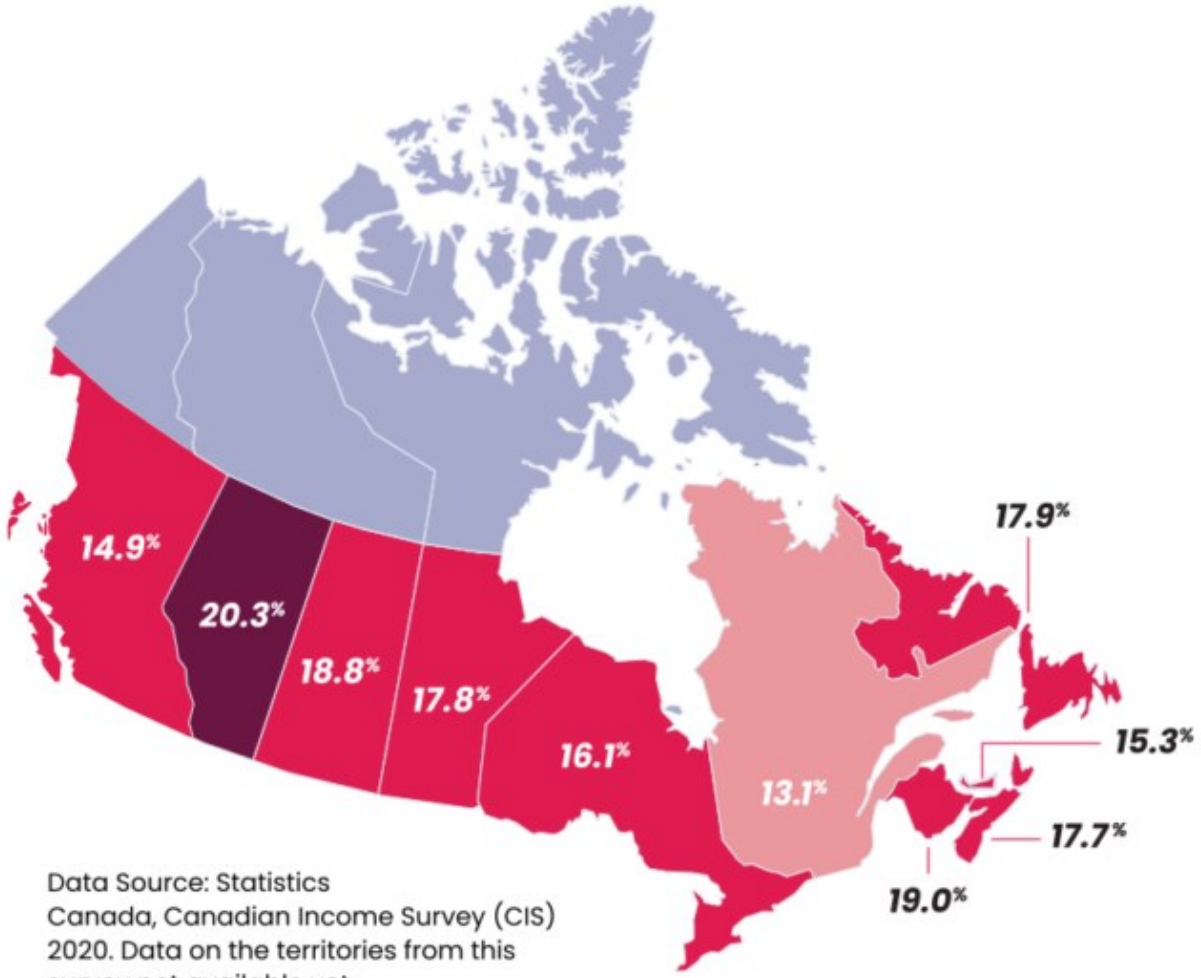
Prevalence of Household Food Insecurity by Province, 2021



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

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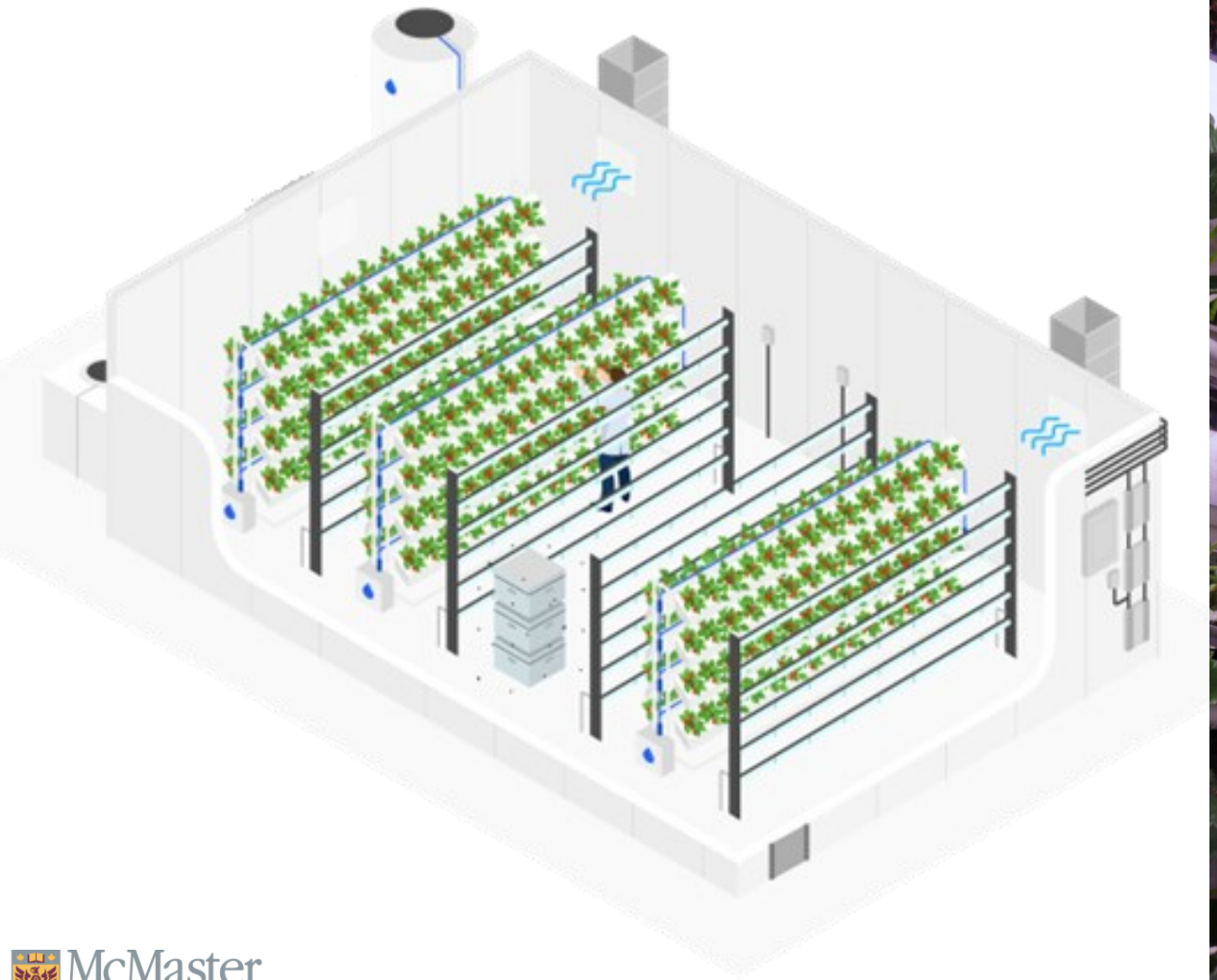
Controlled Environment Agriculture (CEA)



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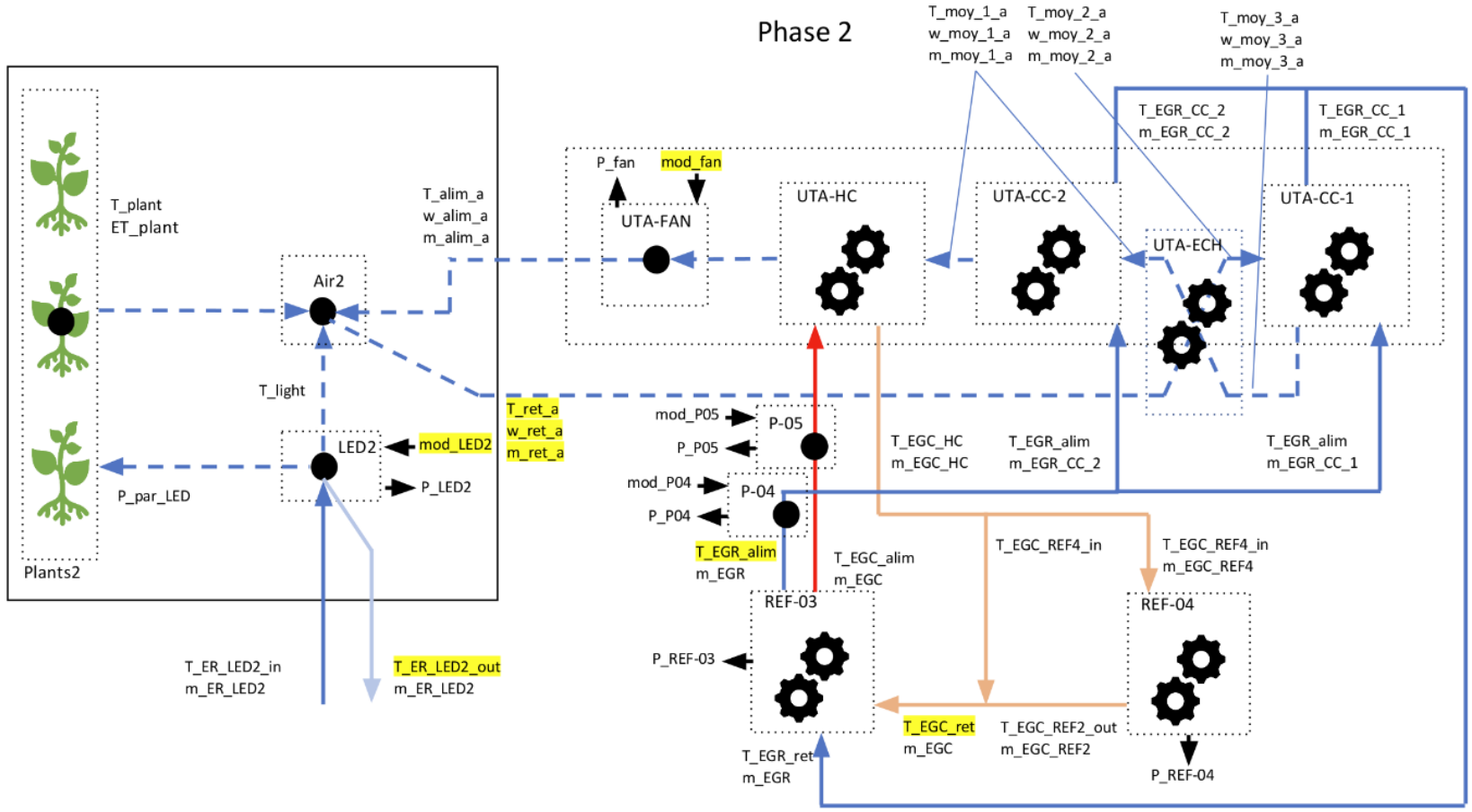
The challenge of CEA: **control is hard**

Maximize crop-to-energy ratio
Reduce waste

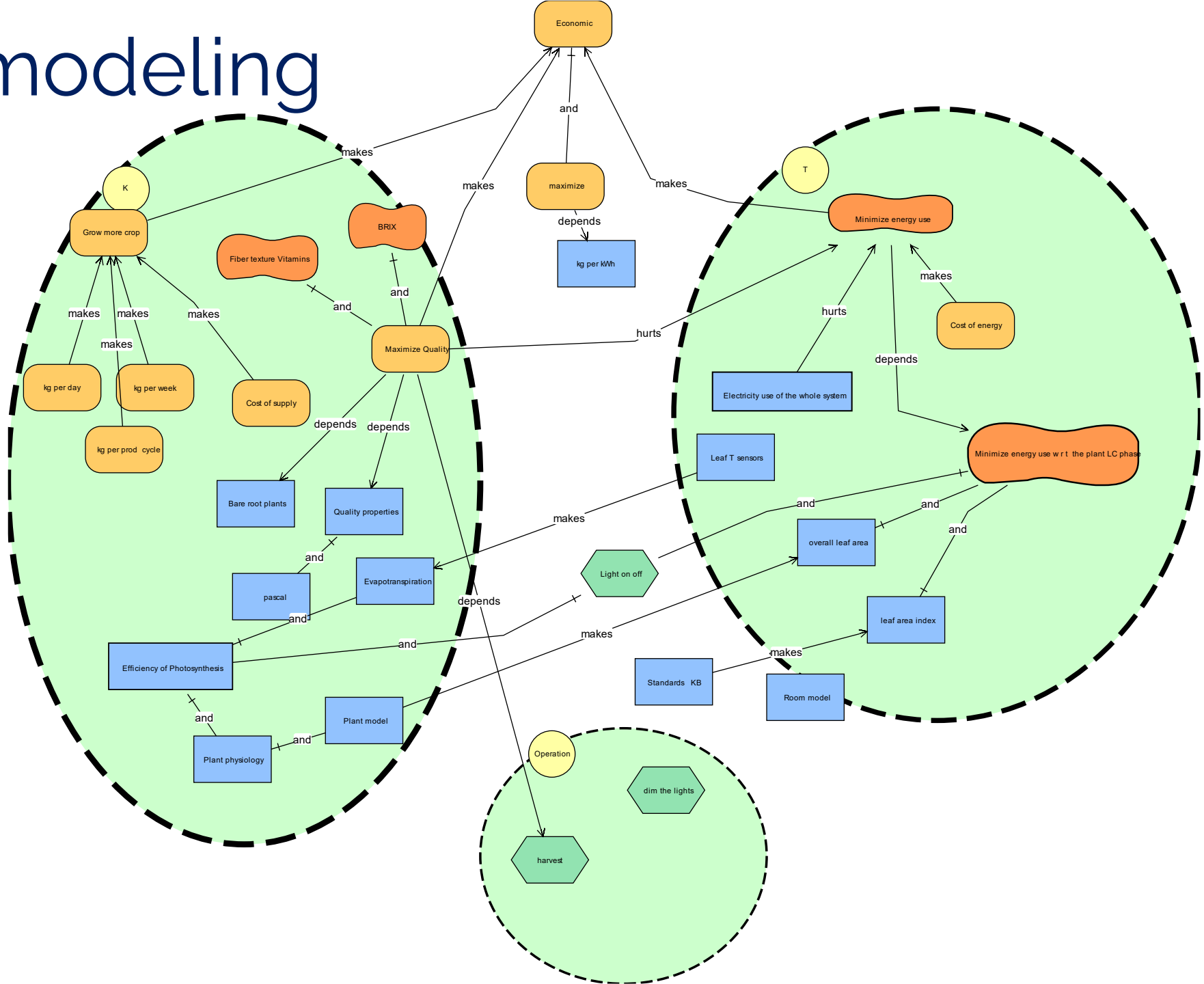
…

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

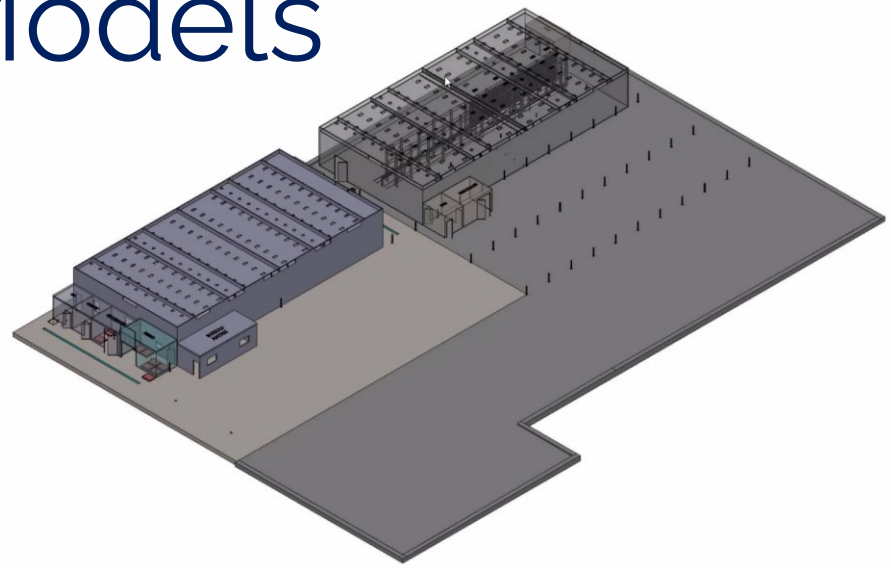
Expressing expert processes

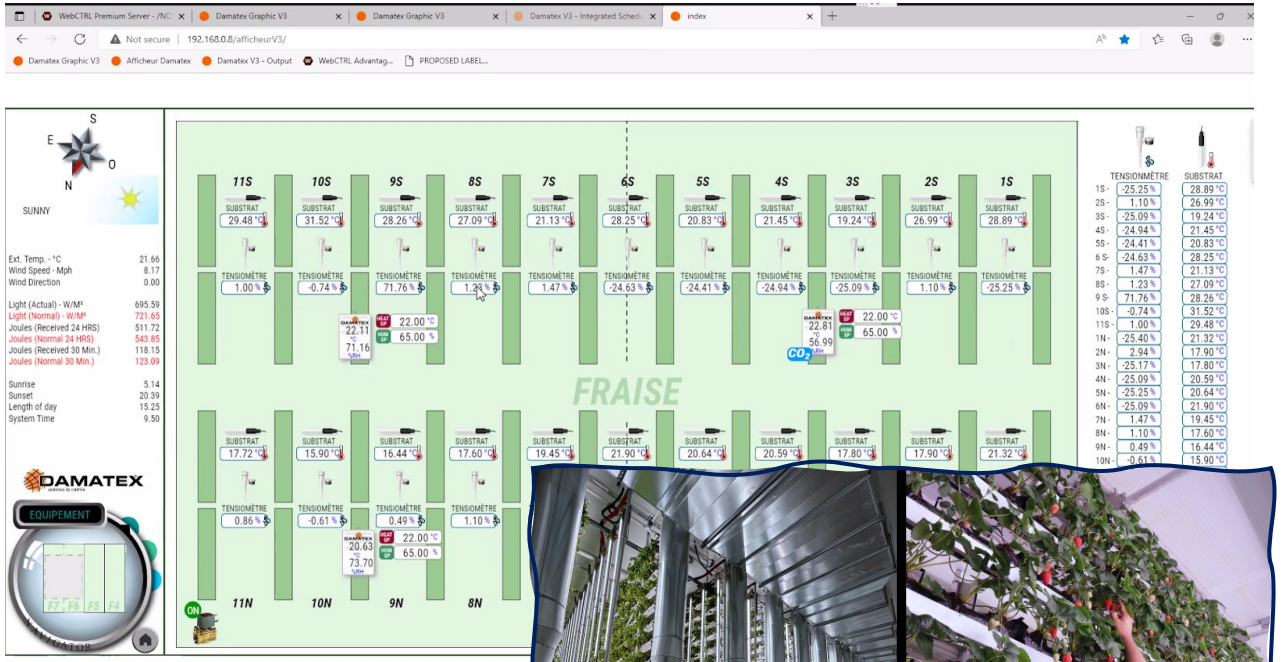


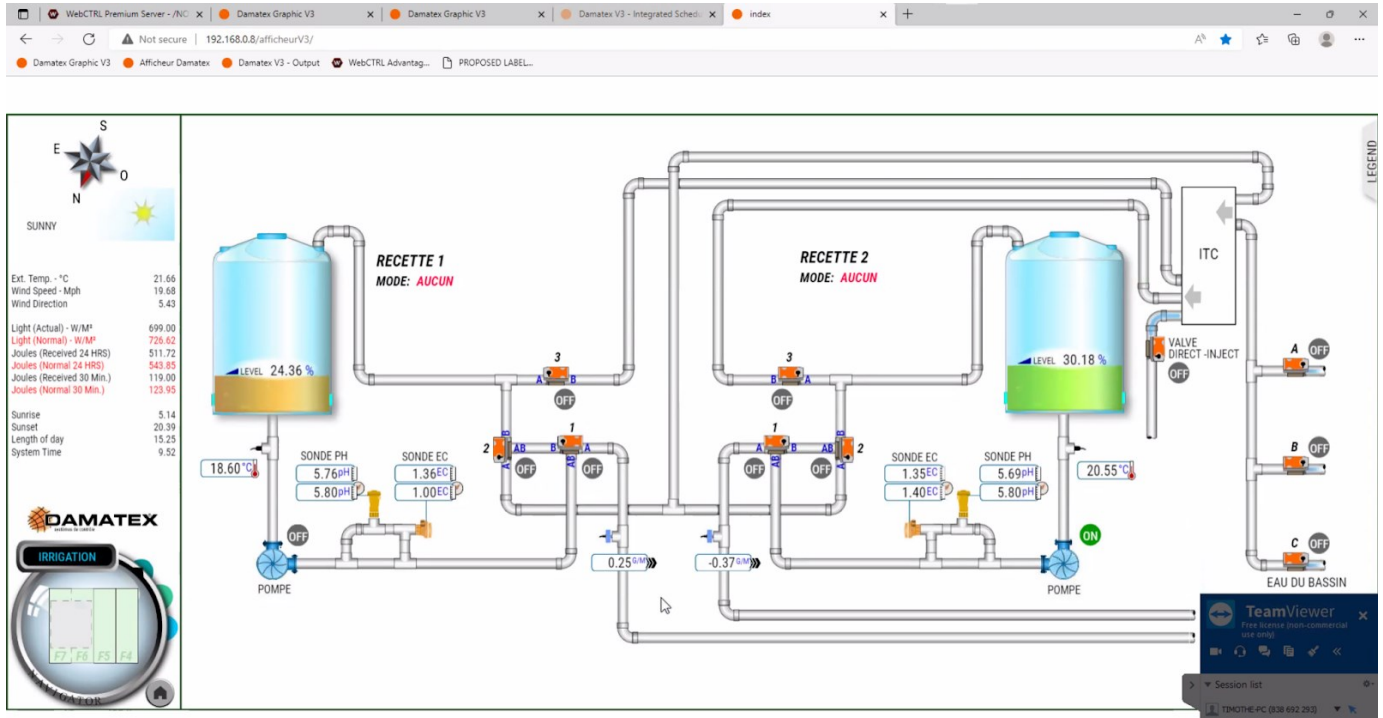
Goal modeling



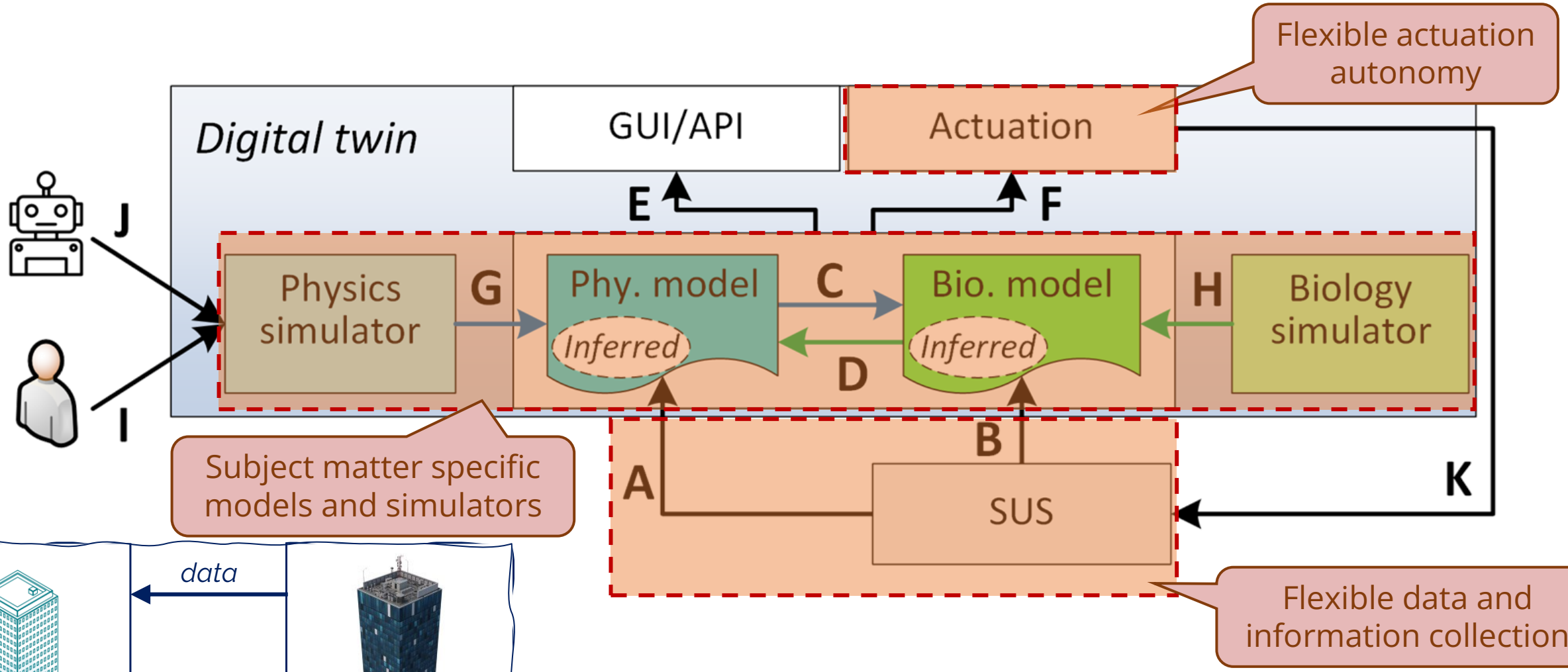
Models

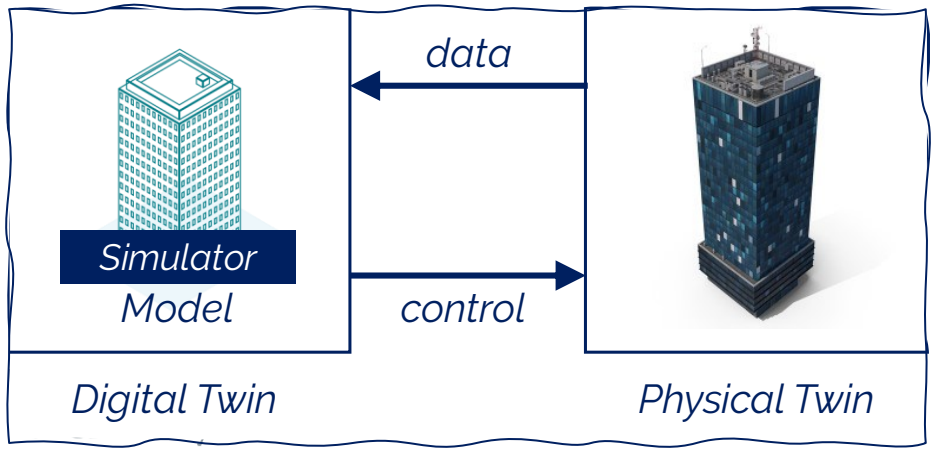



FRAISE
11S
10S
9S
8S
7S
6S
5S
4S
3S
2S
1S
11N
10N
9N
8N
EQUIPEMENT
DAMATEX


RECETTE 1
MODE: AUCUN
RECETTE 2
MODE: AUCUN
ITC
VALVE DIRECT -INJECT
SONDE PH
SONDE EC
POMPE
EAU DU BASSIN
IRRIGATION
DAMATEX
SUNNY
TeamViewer

DT4CBPS: Conceptual framework and requirements





Environment

Room

- HVAC
- Lights
- Irrigation

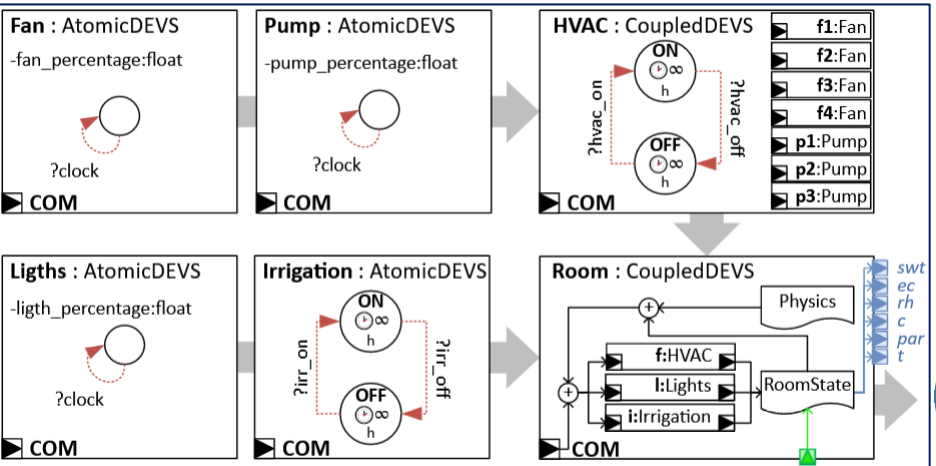
$$\frac{dy}{dt} = ky$$

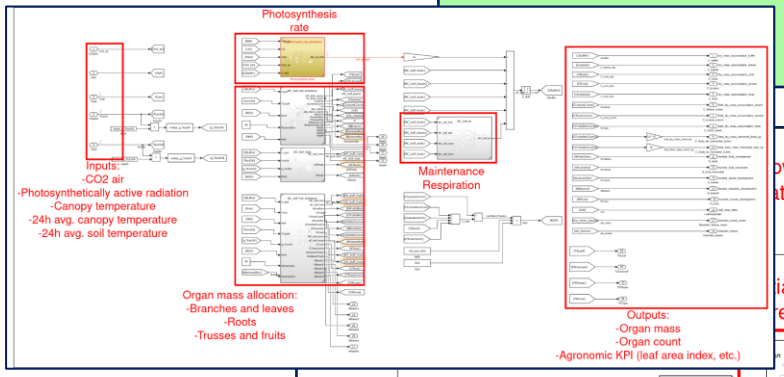
MATLAB®

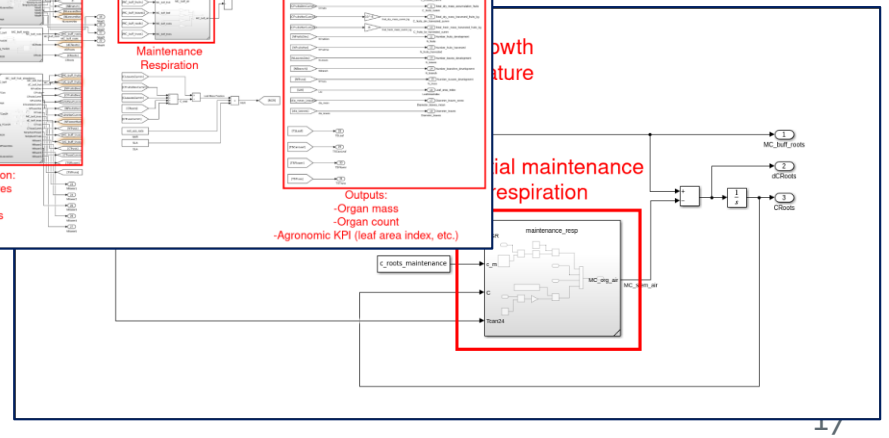
SIMULINK®

Crop

- Energy
- Growth







Ì źţņõõì ÁBÑÛ

Environment

Room

- HVAC
- Lights
- Irrigation

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

fmi Functional Mock-Up Interface

$$\frac{dy}{dt} = ky$$

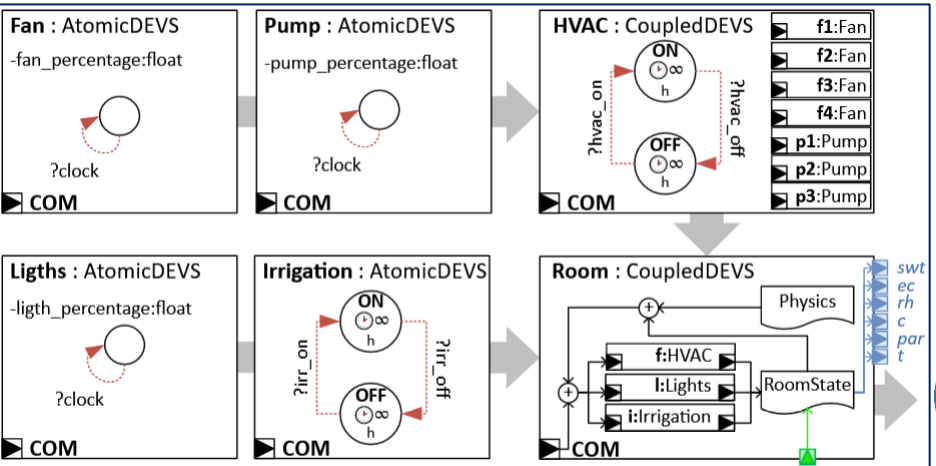
MATLAB®

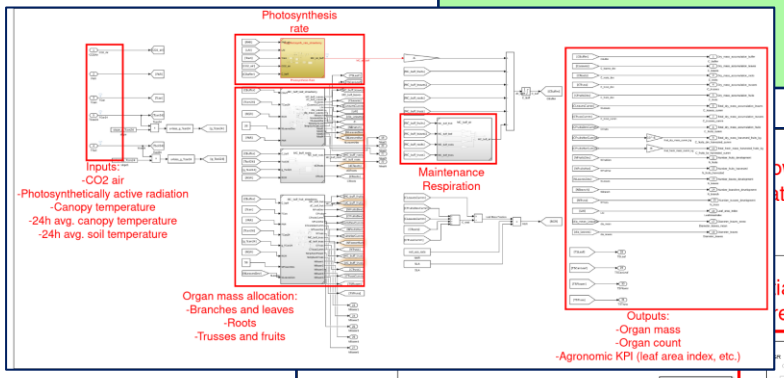
fmi Functional Mock-Up Interface

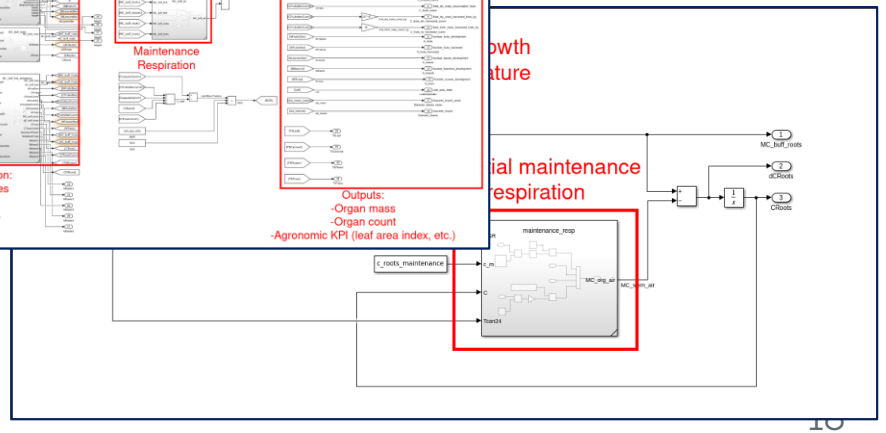
SIMULINK®

Crop

- Energy
- Growth







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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*
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†Ferme d'Hiver Technologies, Canada – {tlalonde,kriaz}@fermedhiver.ca

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

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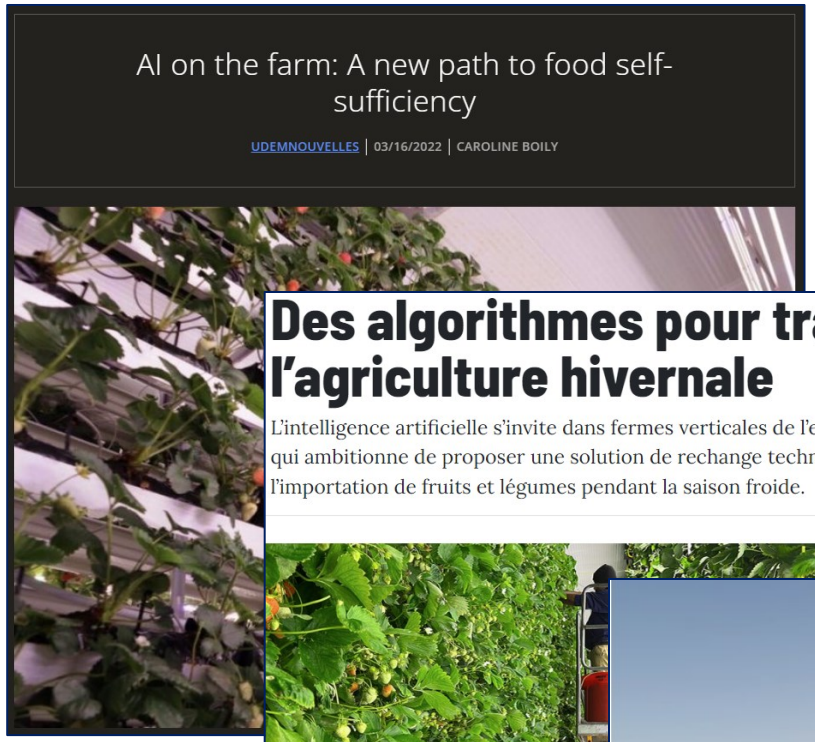


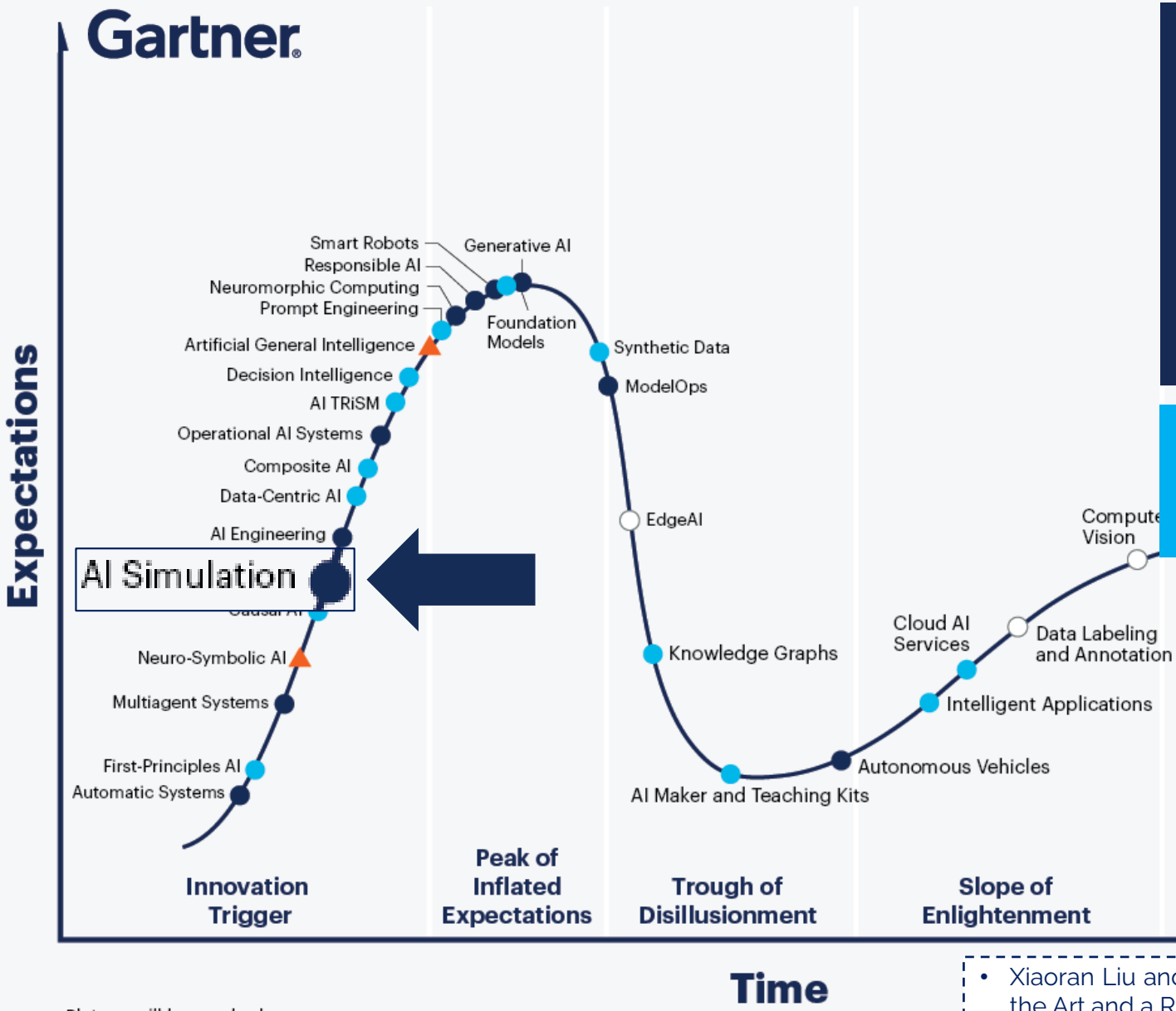
https://nouvelles.umontreal.ca/en/article/2022/03/16/ai-on-the-farm-a-new-path-to-food-self-sufficiency/

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

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


AI Simulation by Digital Twins

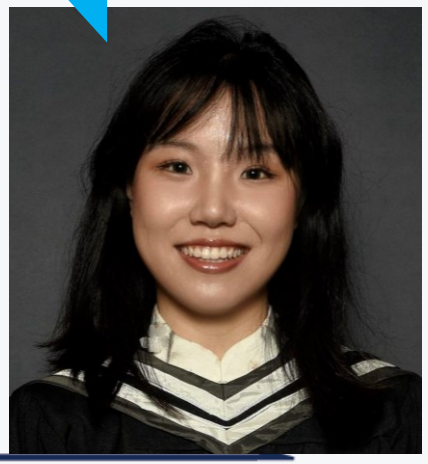
Hype Cycle for Artificial Intelligence, 2023



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.

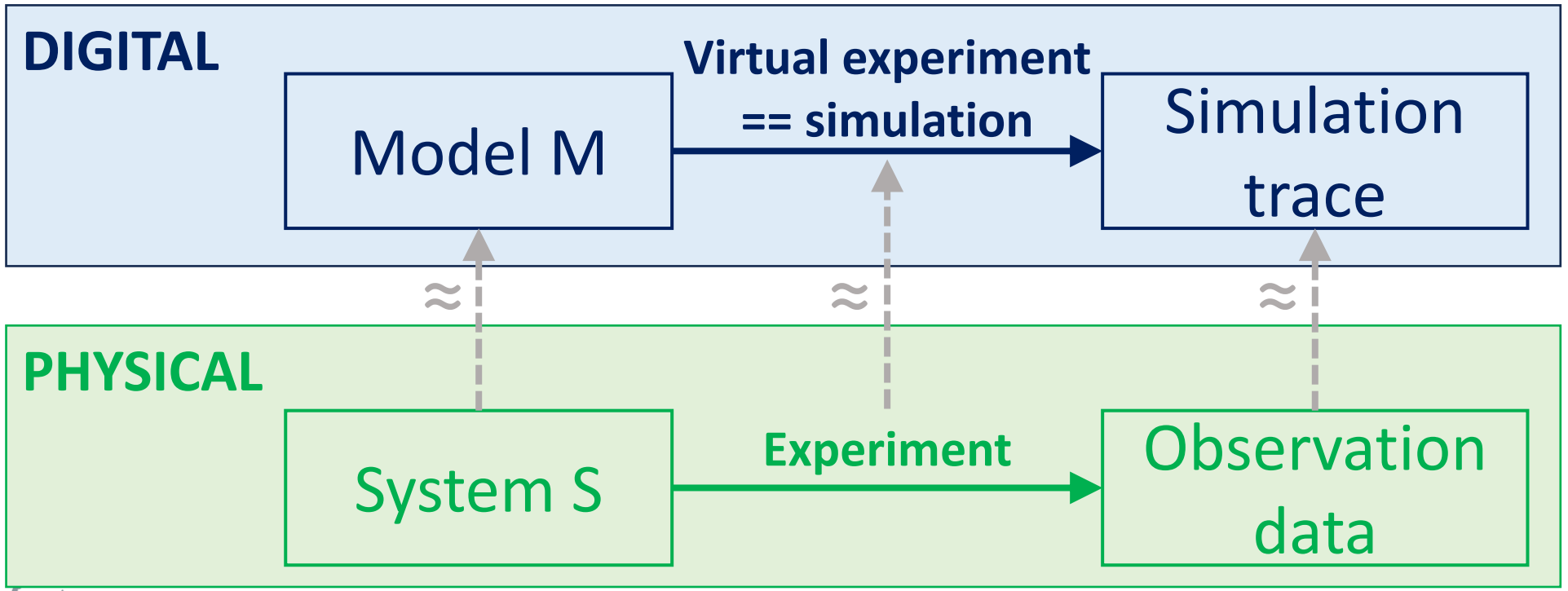
Some of the best simulators today: in DTs



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



Based on:
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- H. Vangheluwe et al. "An introduction to multi-paradigm modelling and simulation." 2002.

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

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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

ACM Reference Format:
Xiaoran Liu and Istvan David. 2024. AI Simulation by Digital Twins: Systematic Survey of the State of the Art and a Reference Framework. In *Proceedings of International Conference on Engineering Digital Twins (EDTConf'24)*. ACM, New York, NY, USA, 12 pages. https://doi.org/XXXXXXX.XXXXXXX

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.

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https://doi.org/XXXXXXX.XXXXXXX

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Domains/problems

Digital twins

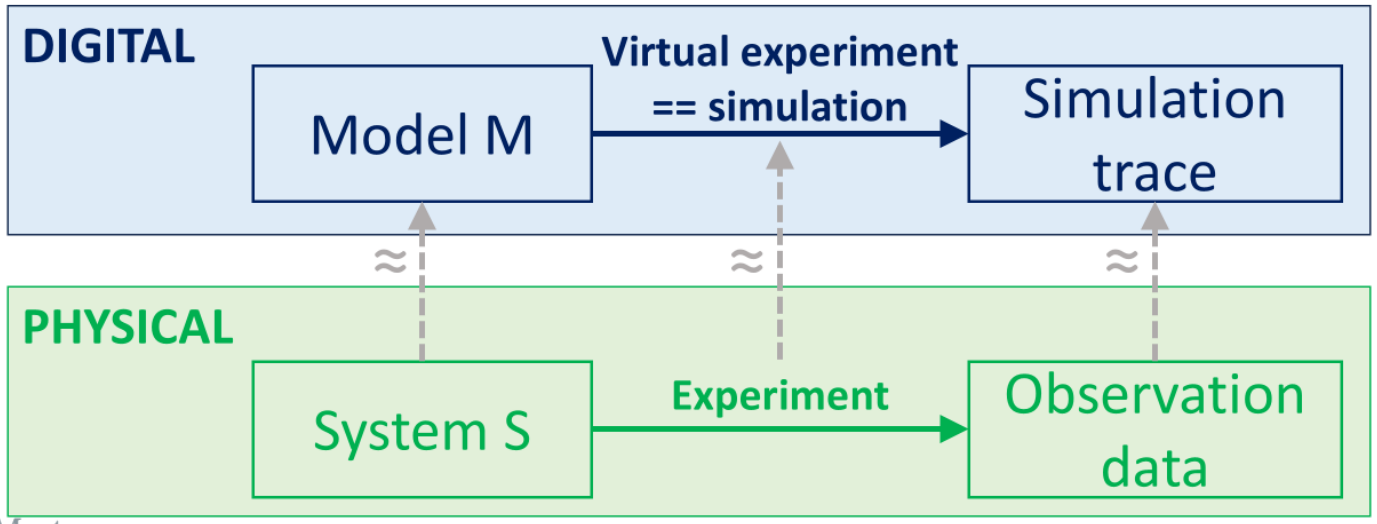
AI/ML

Lifecycle models

Challenges/limitations

DT4AI Reference framework

Opportunity:
purposeful experimentation to acquire missing data



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- H. Vangheluwe et al. "An introduction to multi-paradigm modelling and simulation." 2002.

System

McMaster University

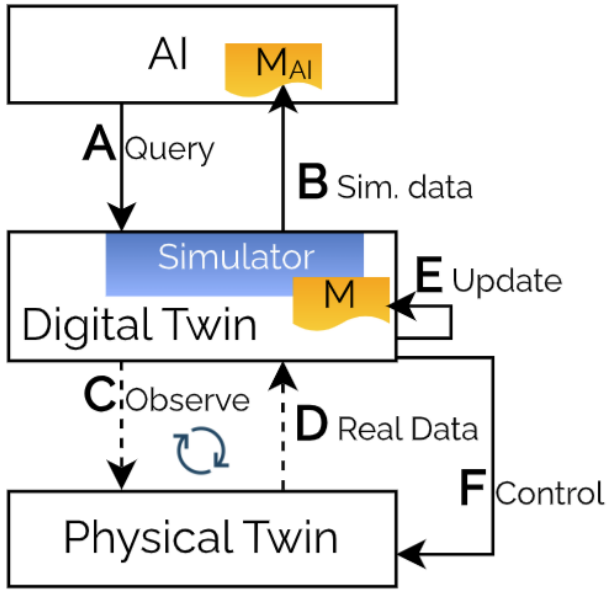
Domains/problems

Digital twins

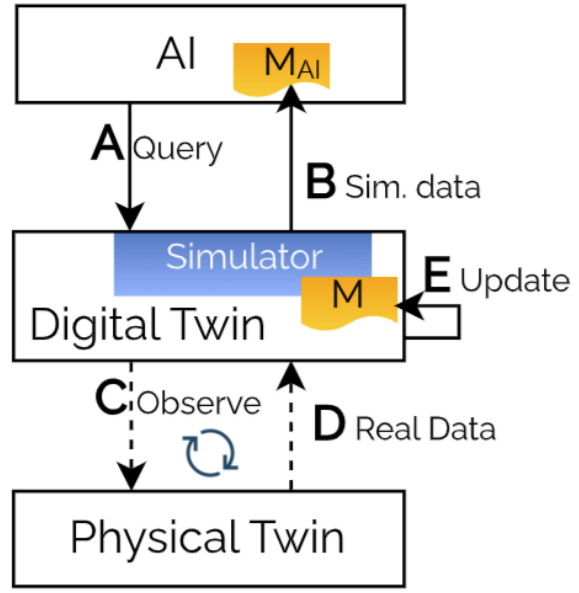
AI/ML

Lifecycle models

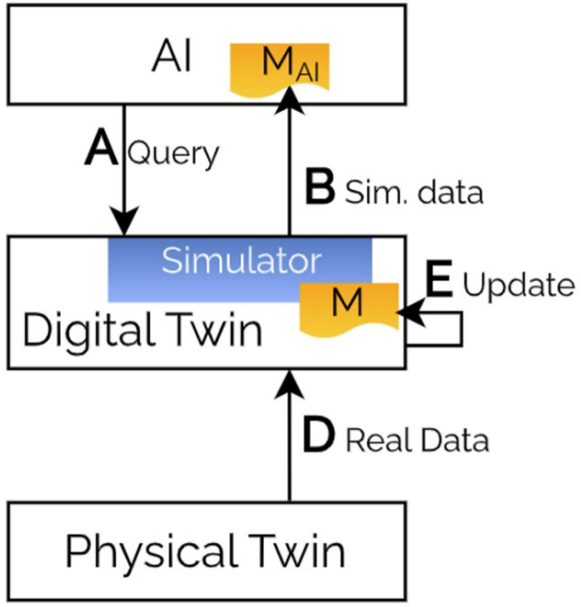
Challenges/limitations



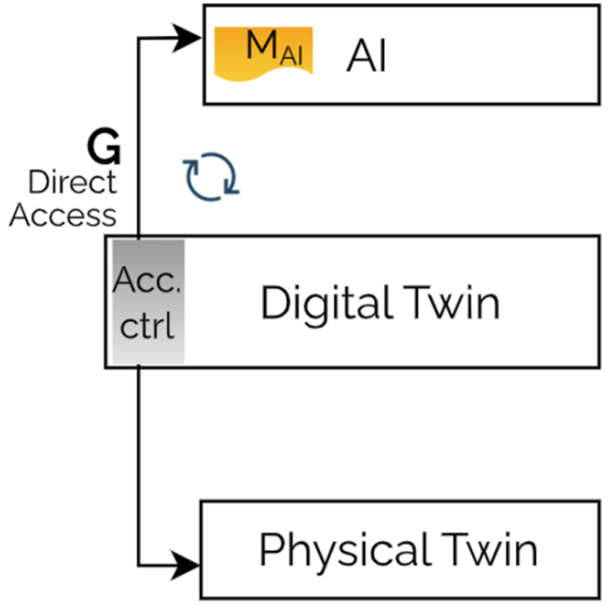
(a) Experimentable DT



(b) Experimentable DS



(c) Experimentable Model



(d) Policy DT

Domains/problems

Digital twins

AI/ML

Lifecycle models

Challenges/limitations

Deep learning proliferates

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]

Domains/problems

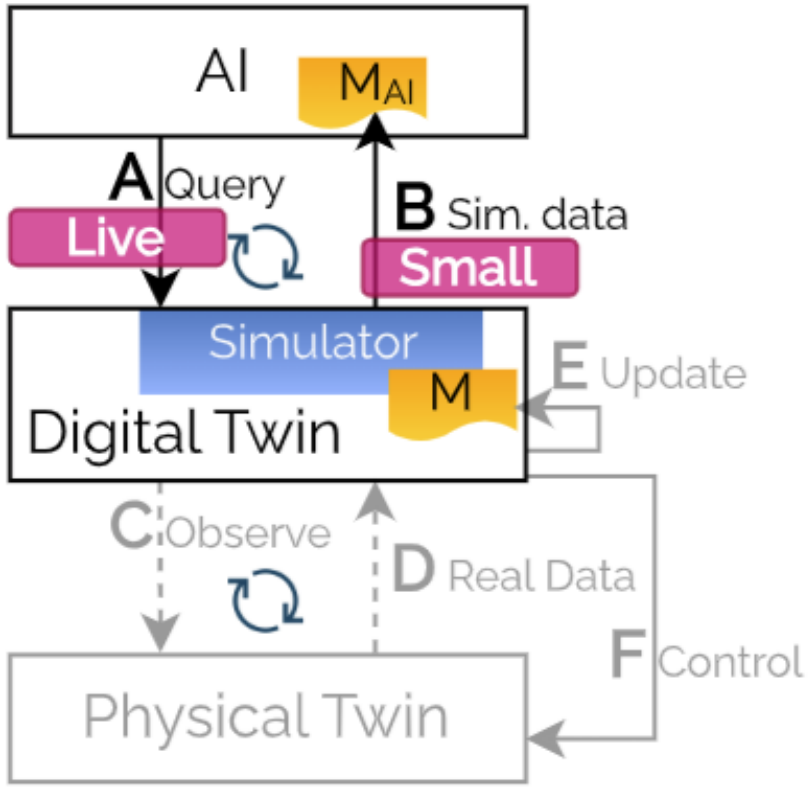
Digital twins

AI/ML

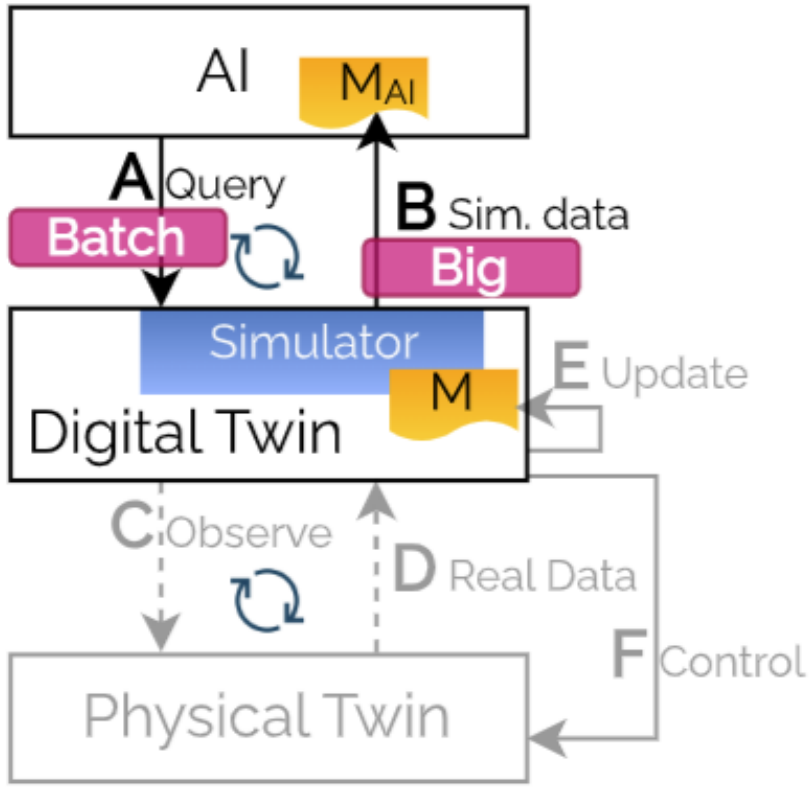
Lifecycle models

Challenges/limitations

Deep learning proliferates



(a) Reinforcement Learning



(b) Deep Learning

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Domains/problems

Digital twins

AI/ML

Lifecycle models

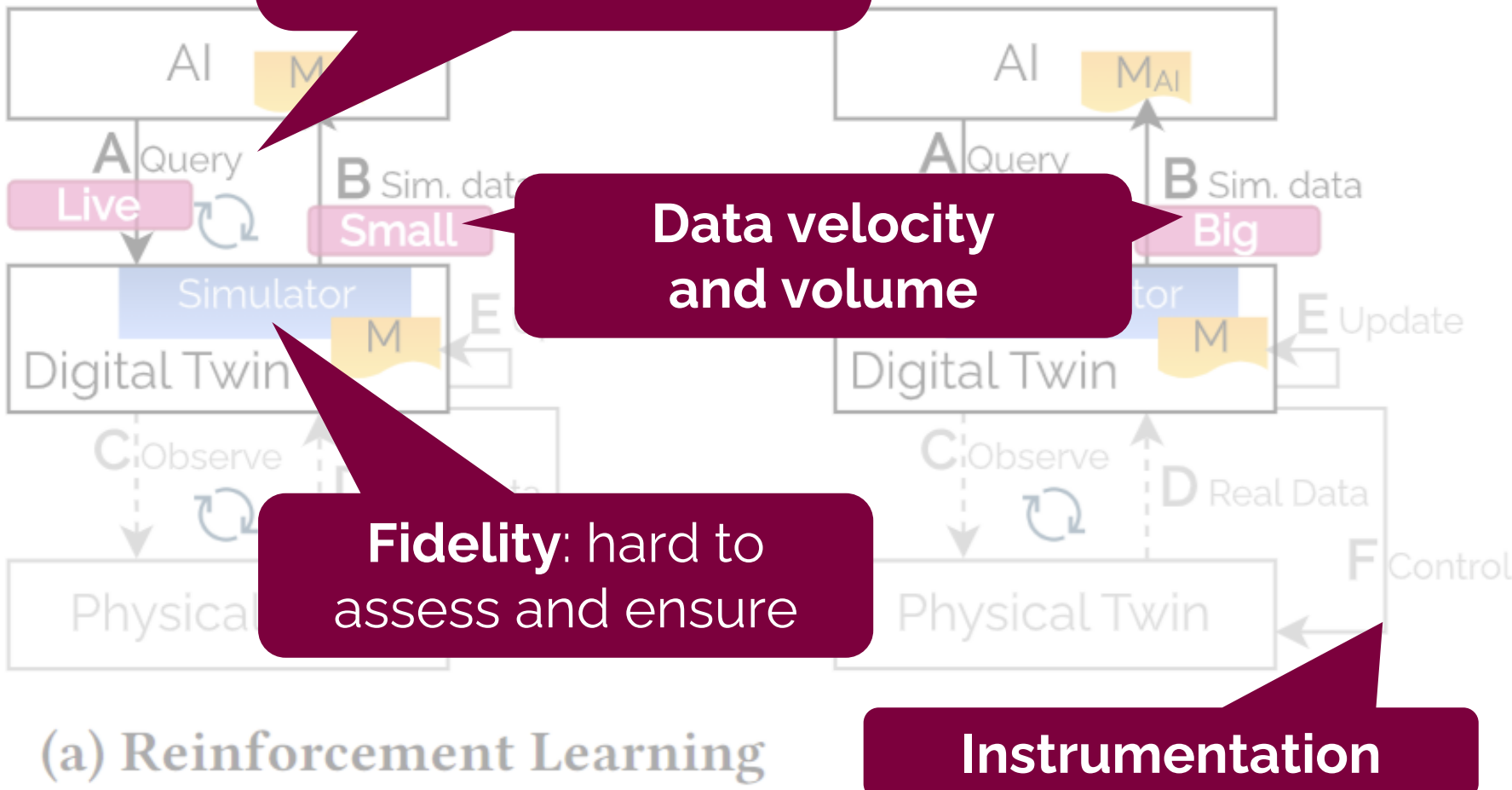
Challenges/limitations

Frequency of interactions: might be limited

Data velocity and volume

Fidelity: hard to assess and ensure

Instrumentation



(a) Reinforcement Learning

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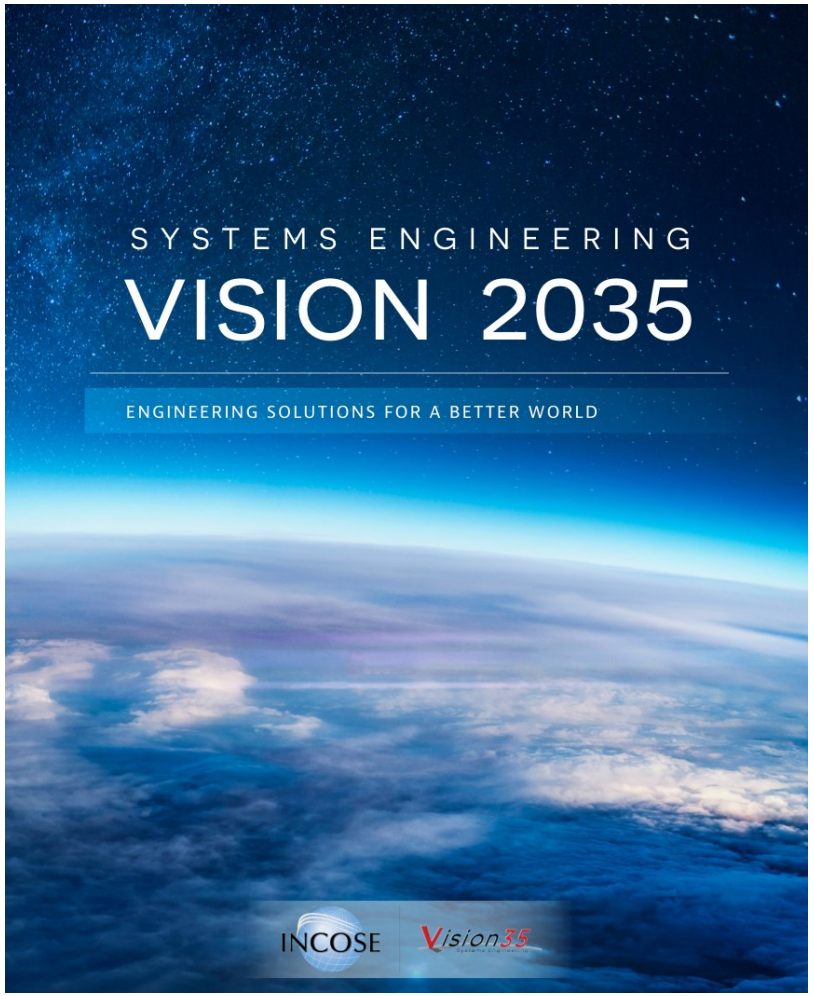
Systems of Twinned Systems

GLOBAL MEGATREND 5

SYSTEM COMPLEXITY EXPLODES

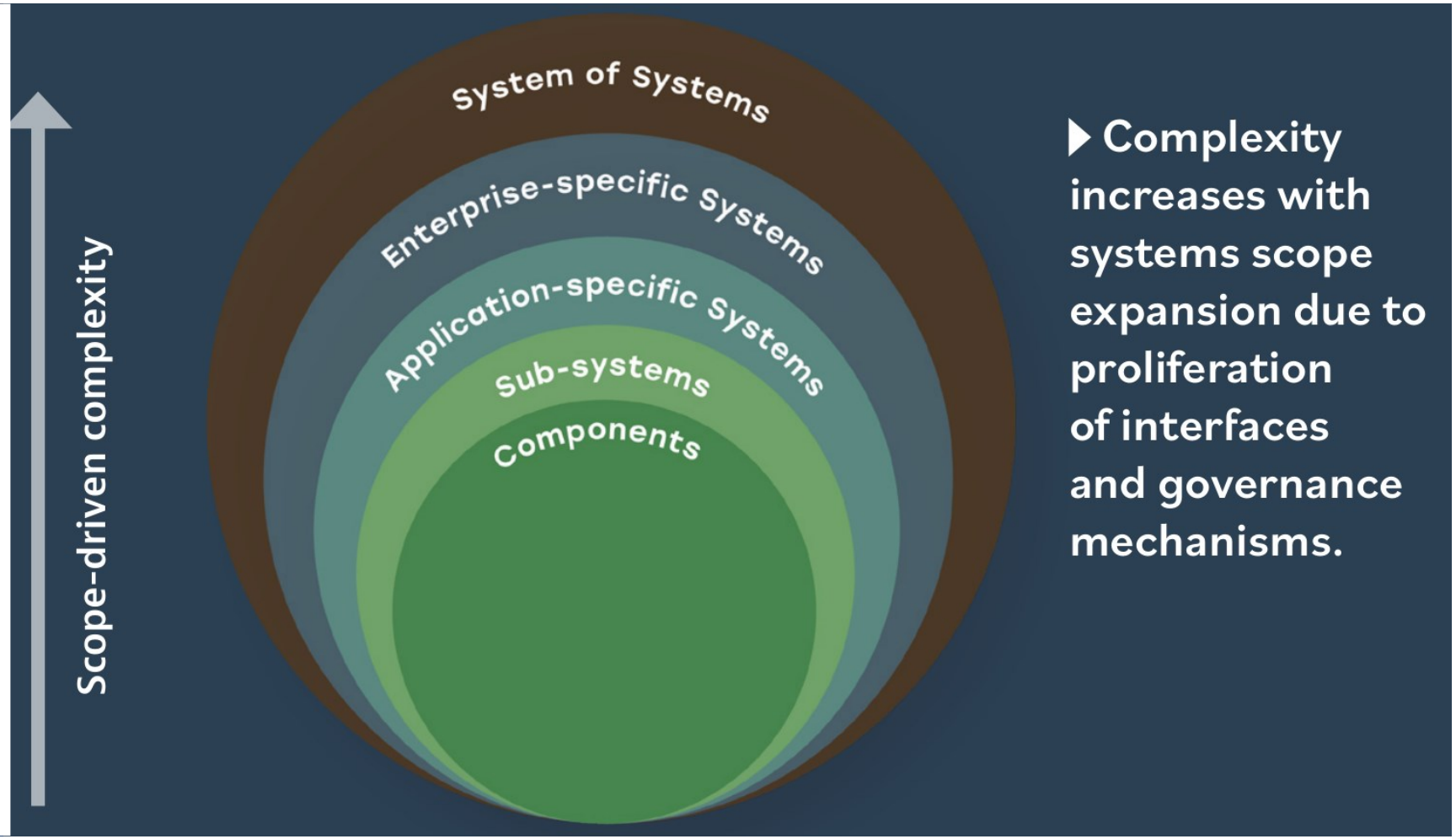


GLOBAL 5 MEGATREND

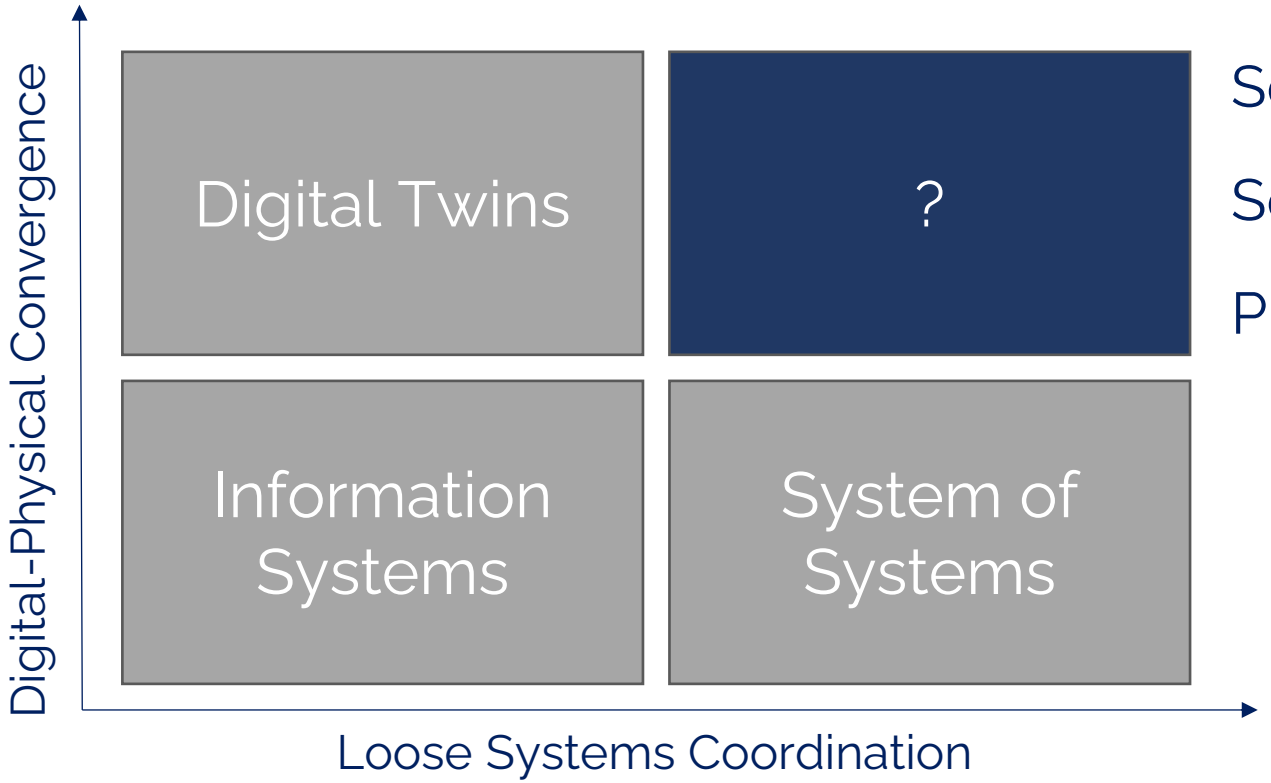
SYSTEM COMPLEXITY EXPLODES

GLOBAL MEGATREND 5

SYSTEM COMPLEXITY EXPLODES



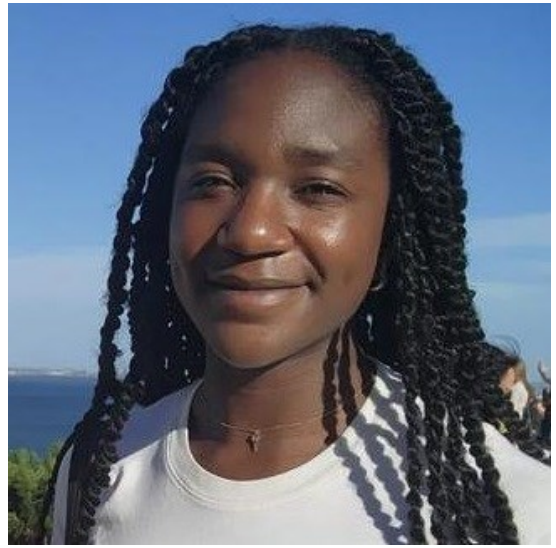
Digital Twins + System of Systems



Scalable integration

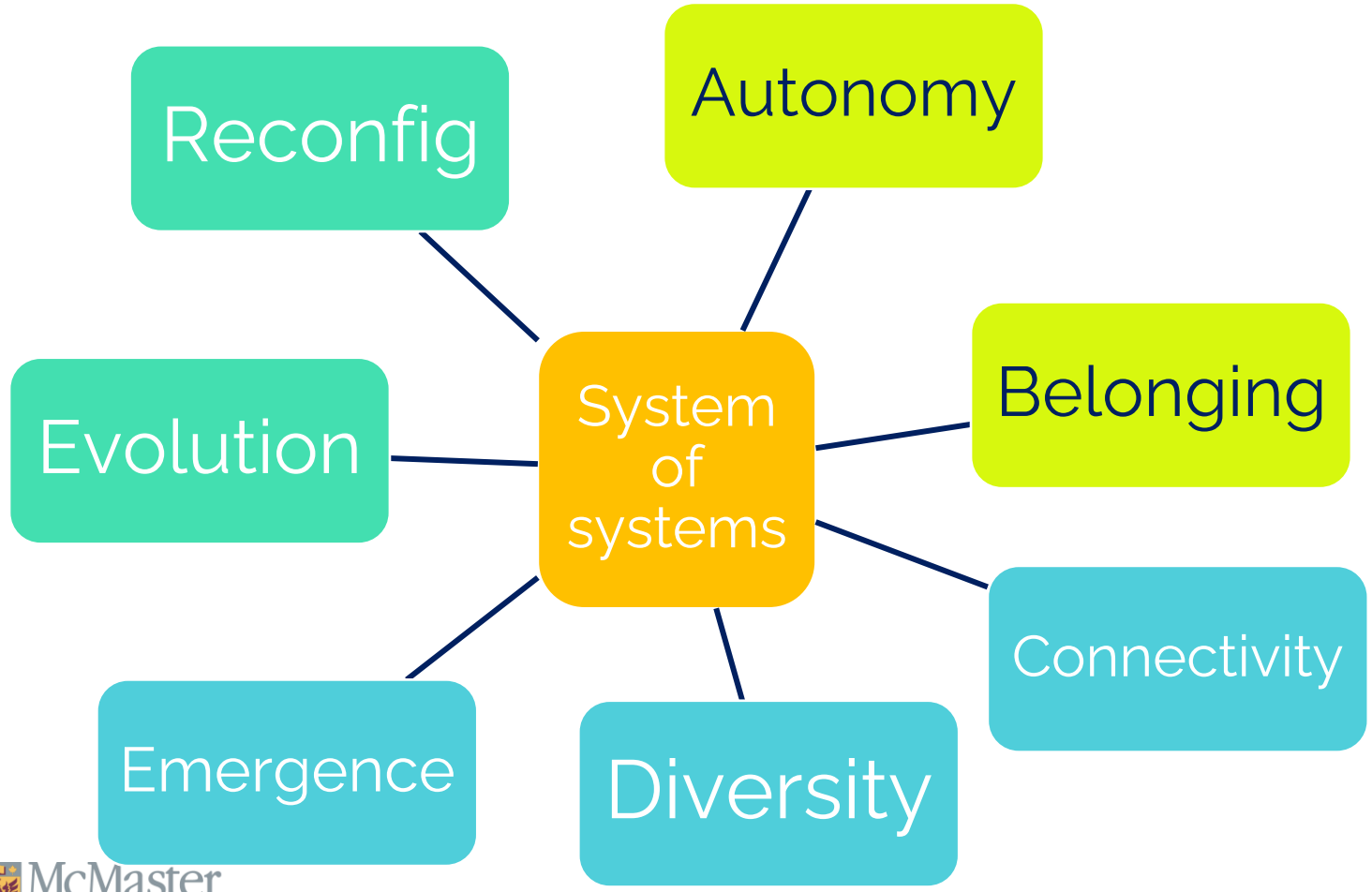
Scalable integration

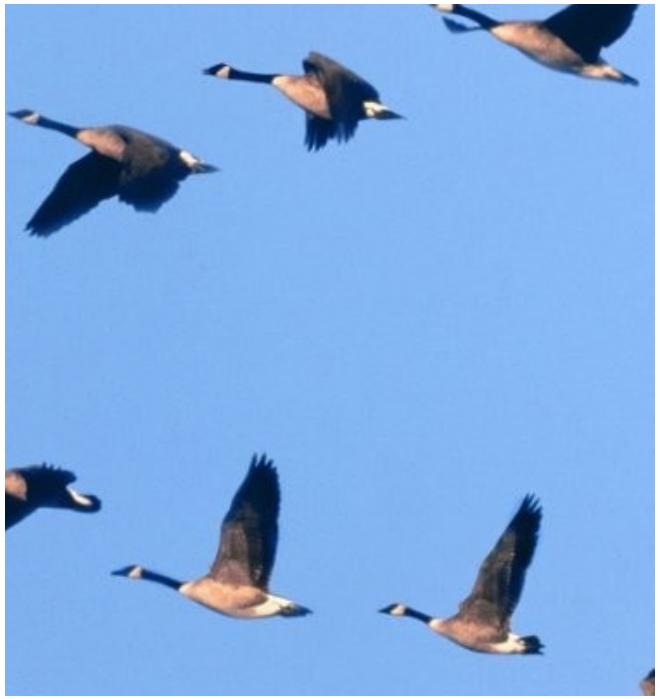
Purposeful engineering of emergent behavior



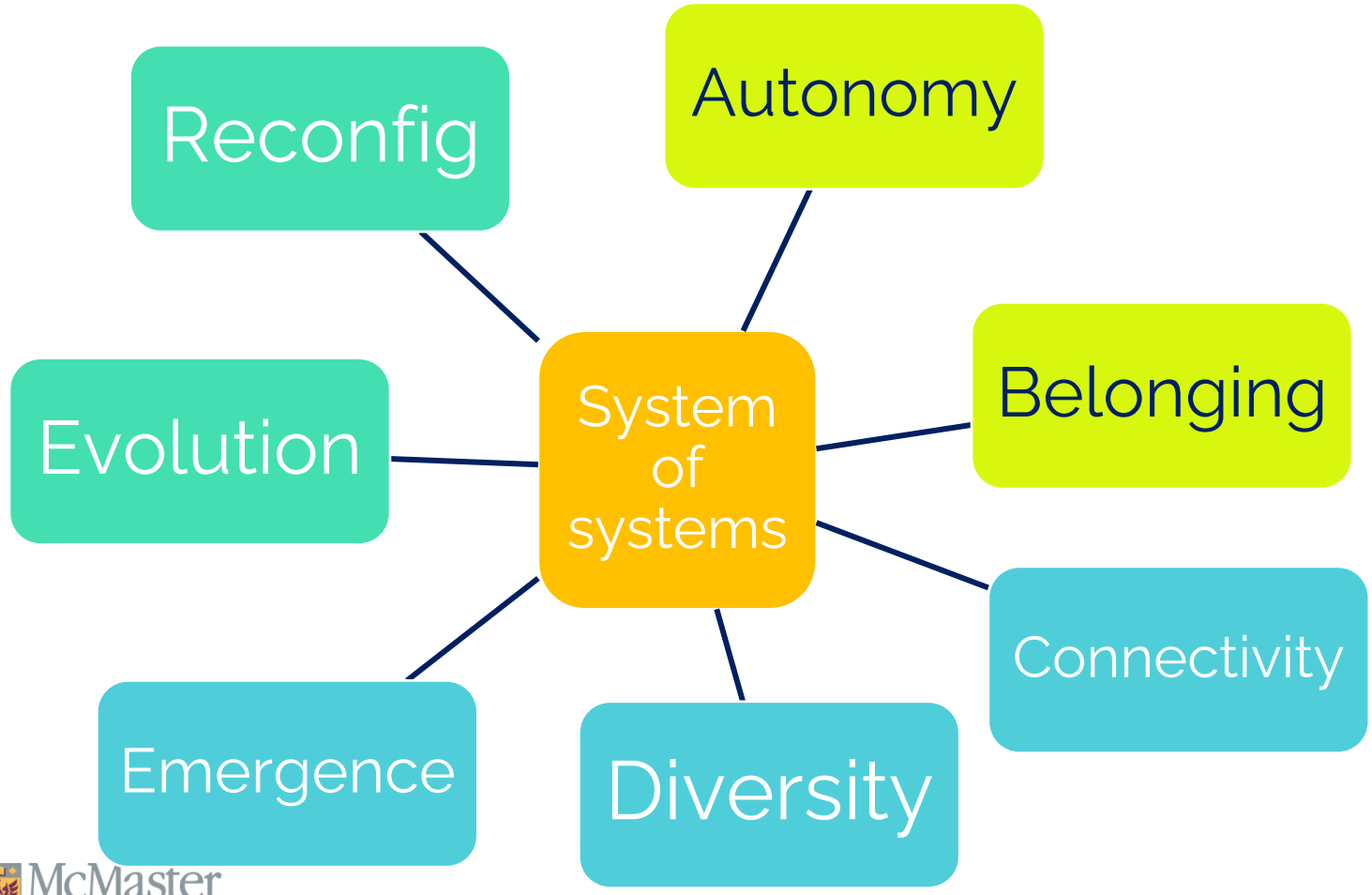
Feyi Adesanya

Characteristics of SoS





Characteristics of SoS



Digital twins and sustainability

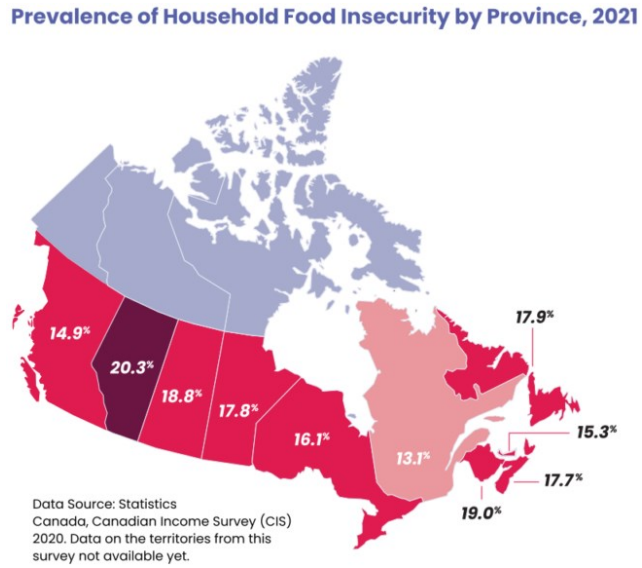
Problem: our systems and methods are not sustainable

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*

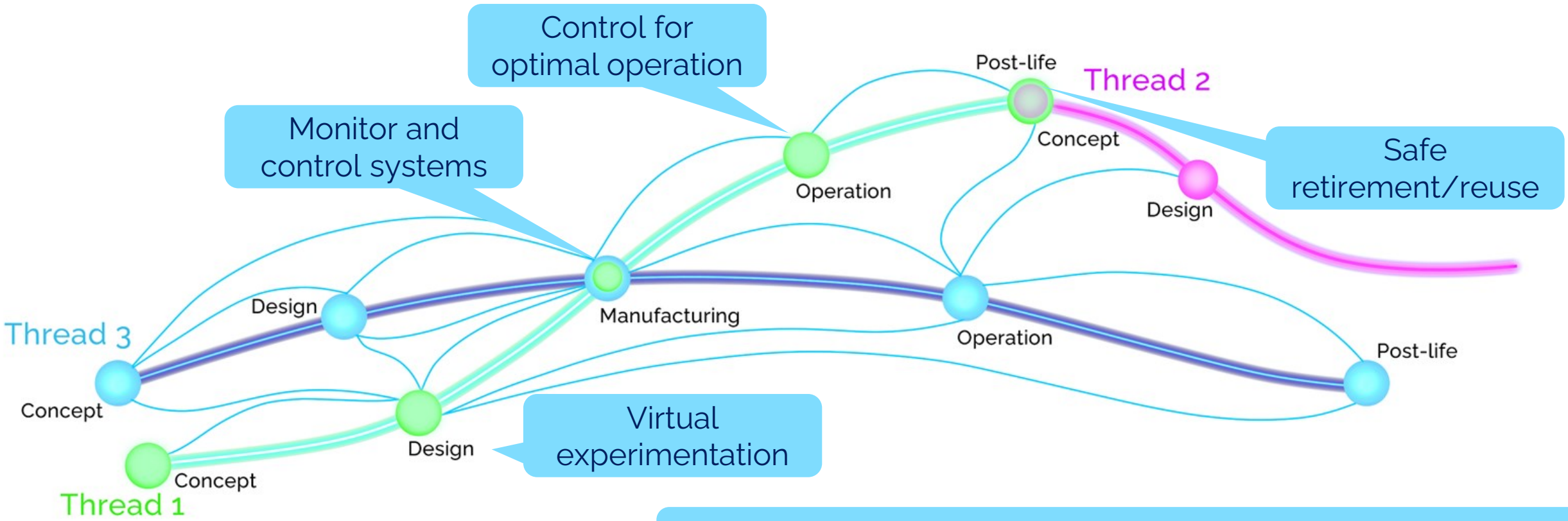
P. Lago, S. A. Koçak, I. Crnkovic, and B. Penzenstadler. *Framing Sustainability as a Property of Software Quality*, Commun. ACM, vol. 58, no. 10, pp. 70–78, Sep. 2015.



Digital Twins for Sustainable Systems

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

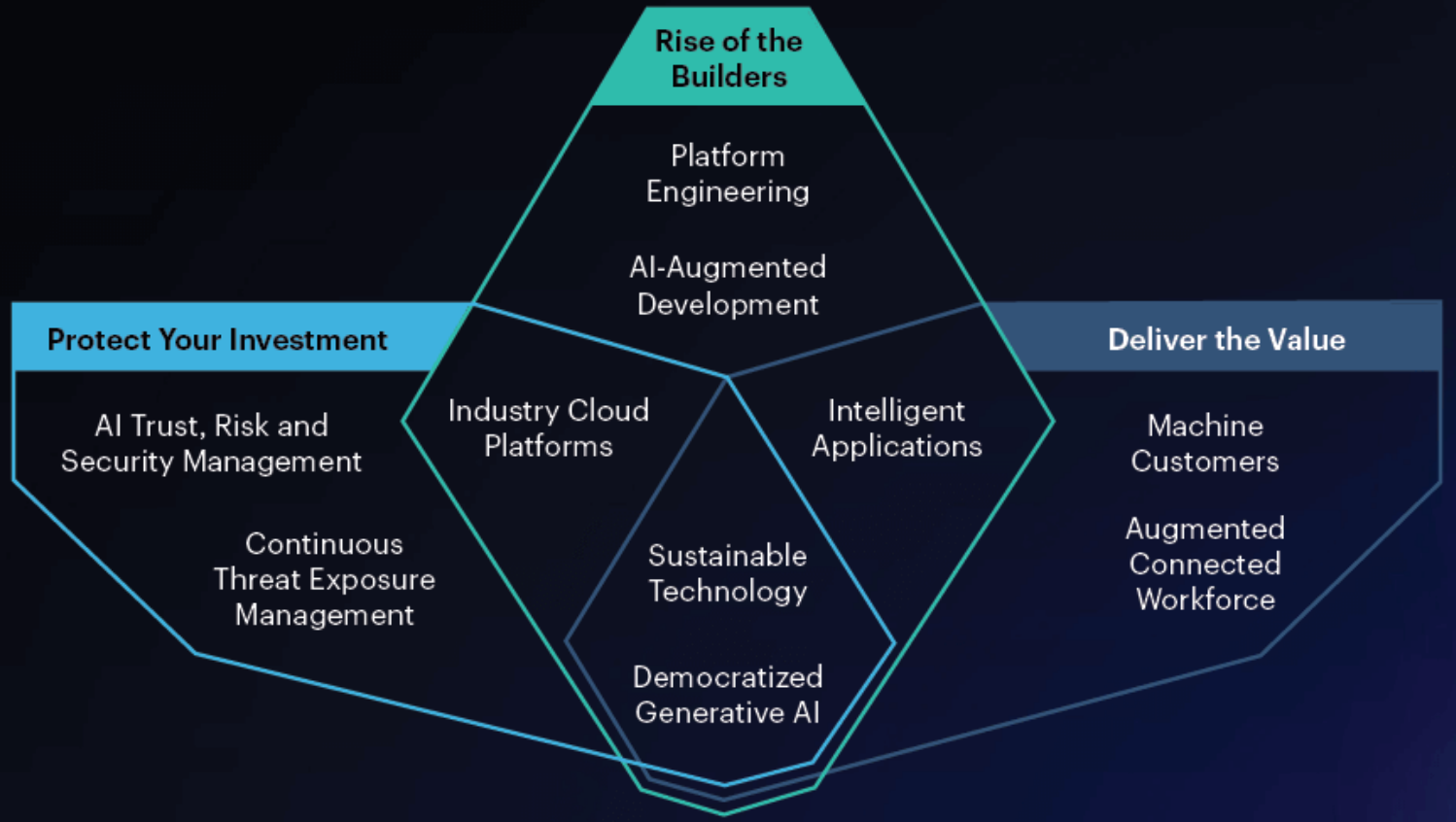
(CapGemini, 2022)



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



Source: Gartner

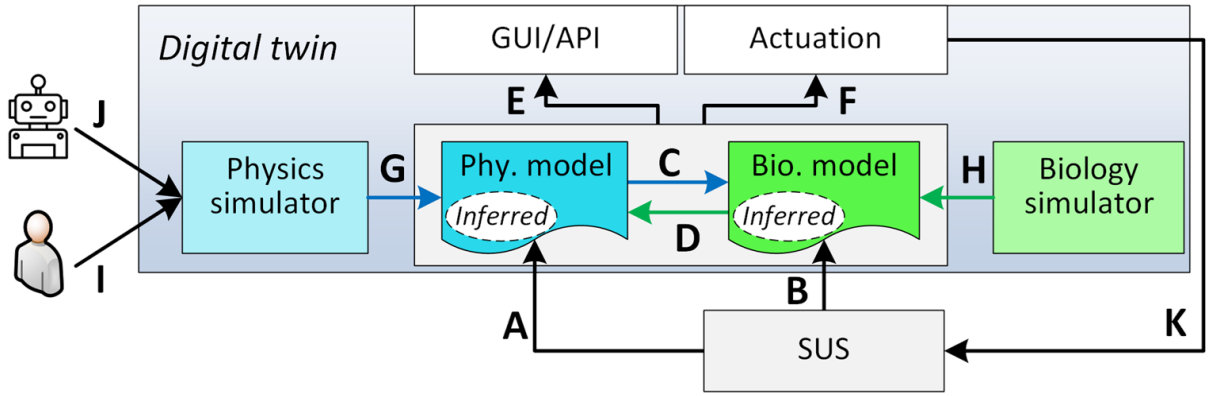
Gartner

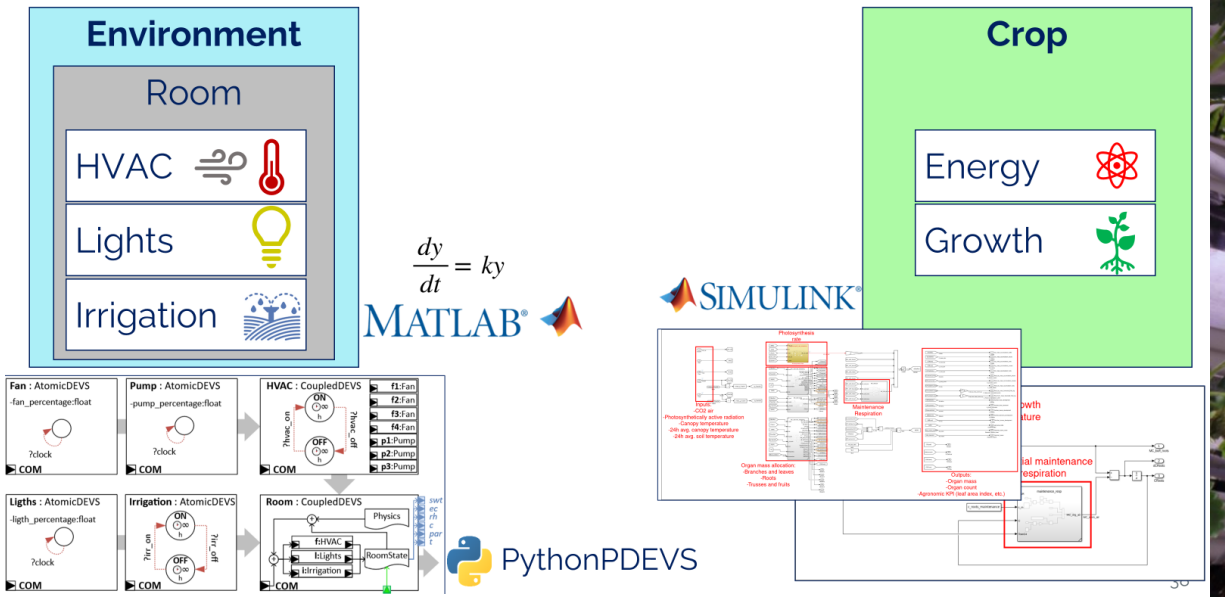
Top Strategic Technology Trends 2024

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

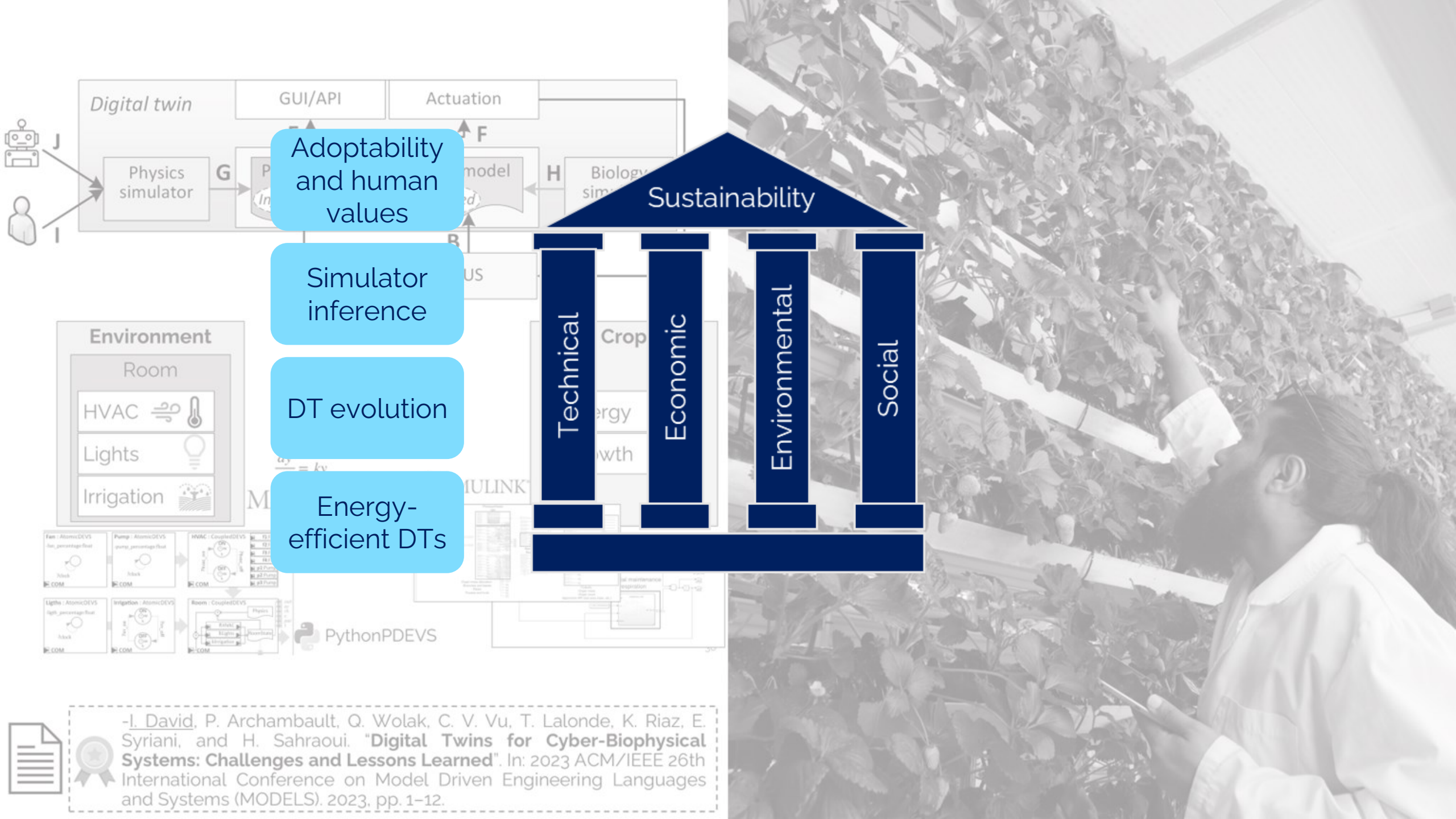
Source: Gartner

Gartner





-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.



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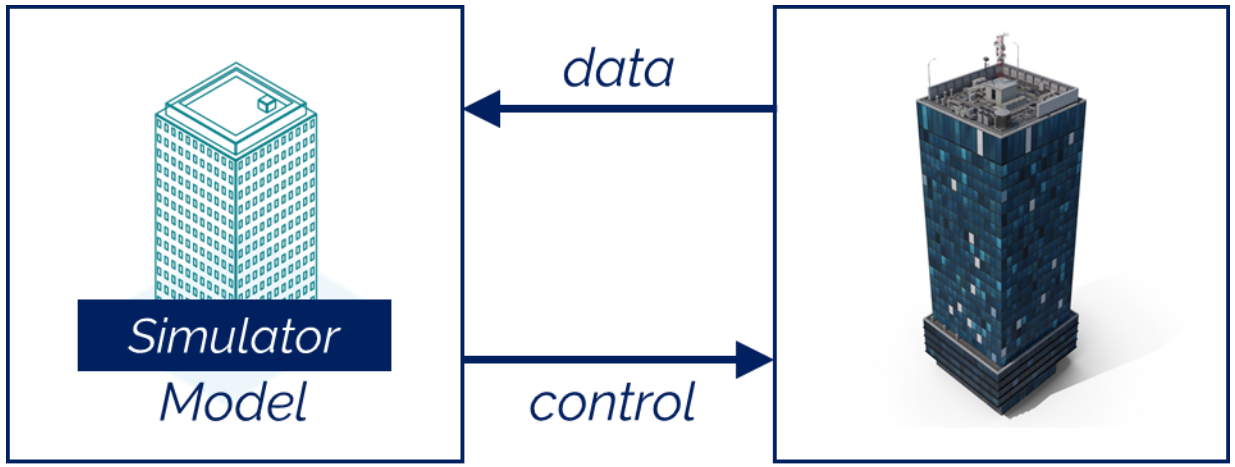
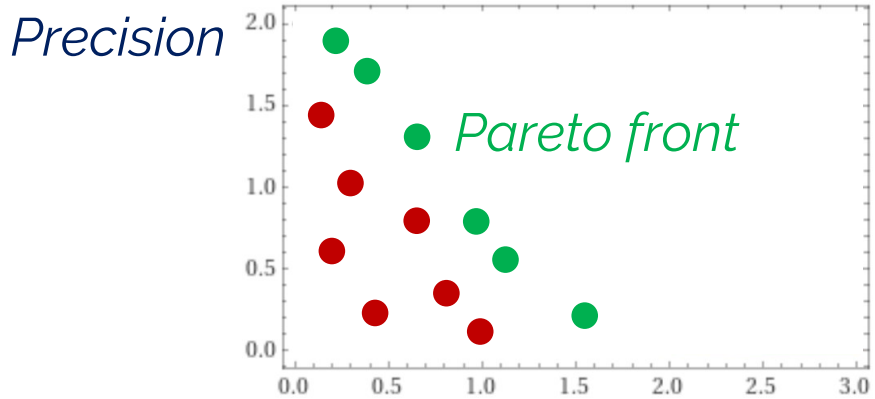
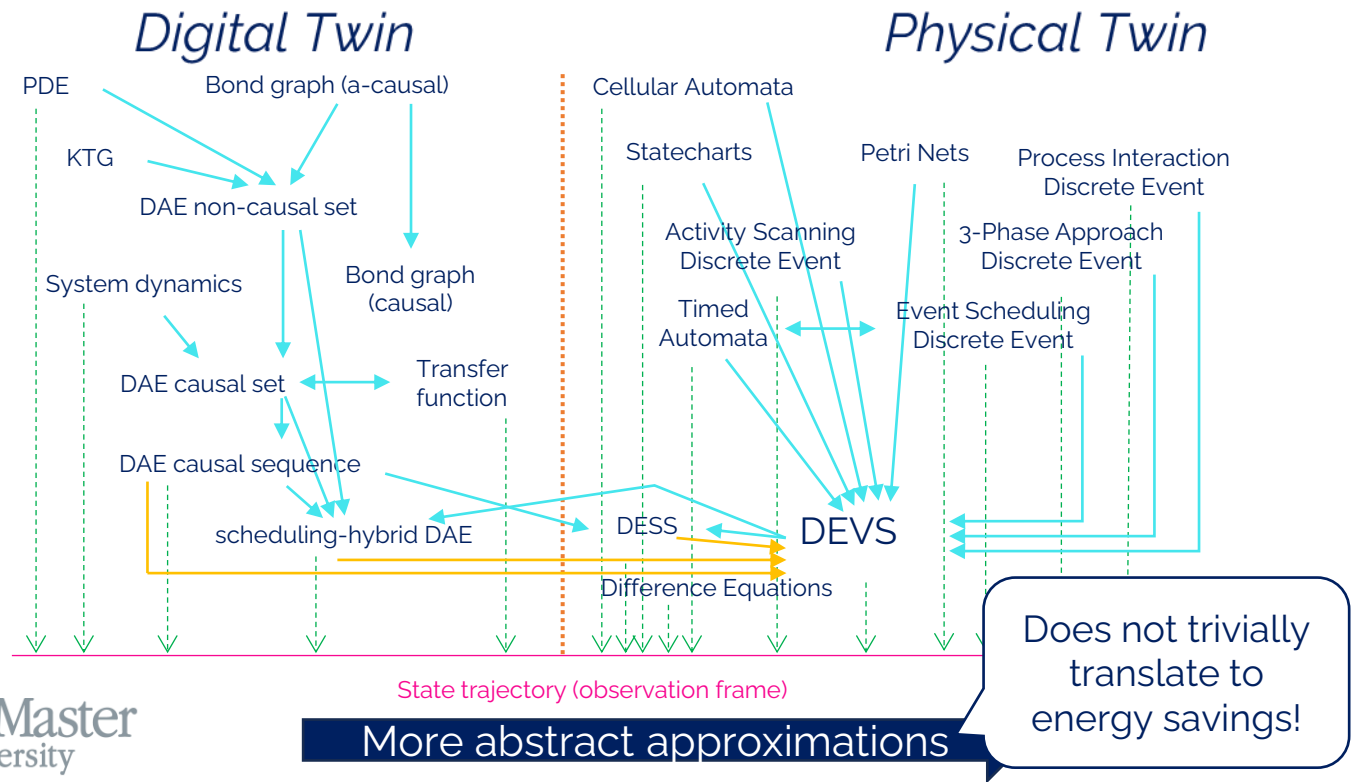
Energy-efficiency of Digital Twins







Does not trivially translate to energy savings!

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)
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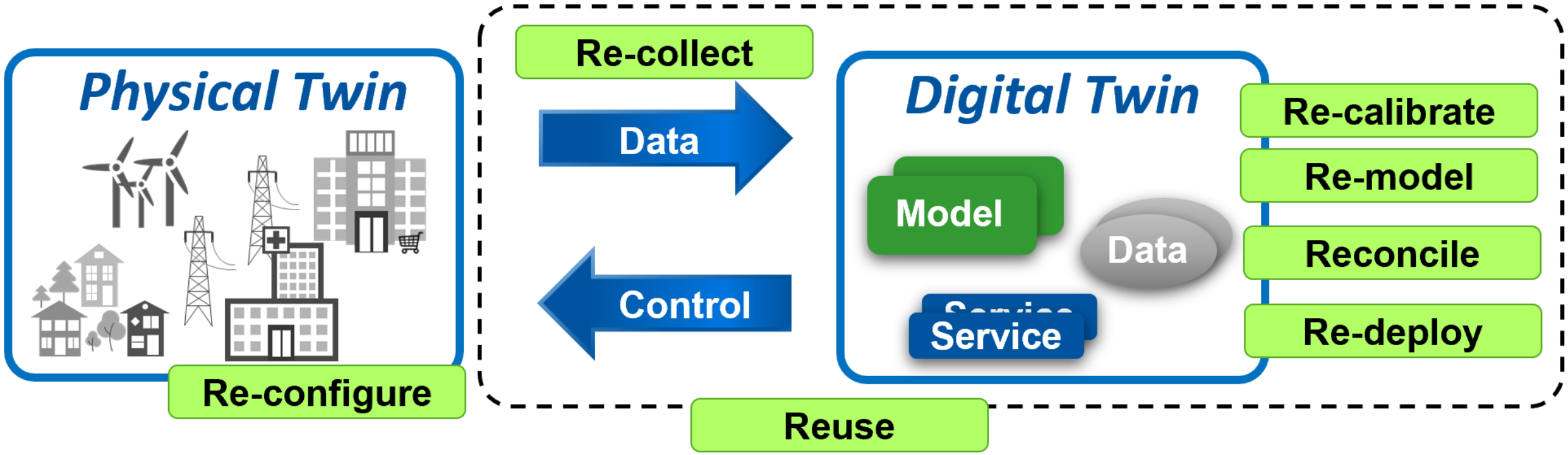
Remove external transition	$removeExtTransition(M, \delta \in \Delta_{ext}) : M' = M \mid \Delta_{int} \setminus \{\delta\}$	(13)
Time advance actions		
Set time advance	$updateTa(M, s, t' \in \mathbb{R}^{+}_{0,+\infty}) : M' = M \mid ta(s) = t'$	(14)
Interacting with other models		
Add output	$addOutput(M, y) : M' = M \mid Y \cup \{y\}$	(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

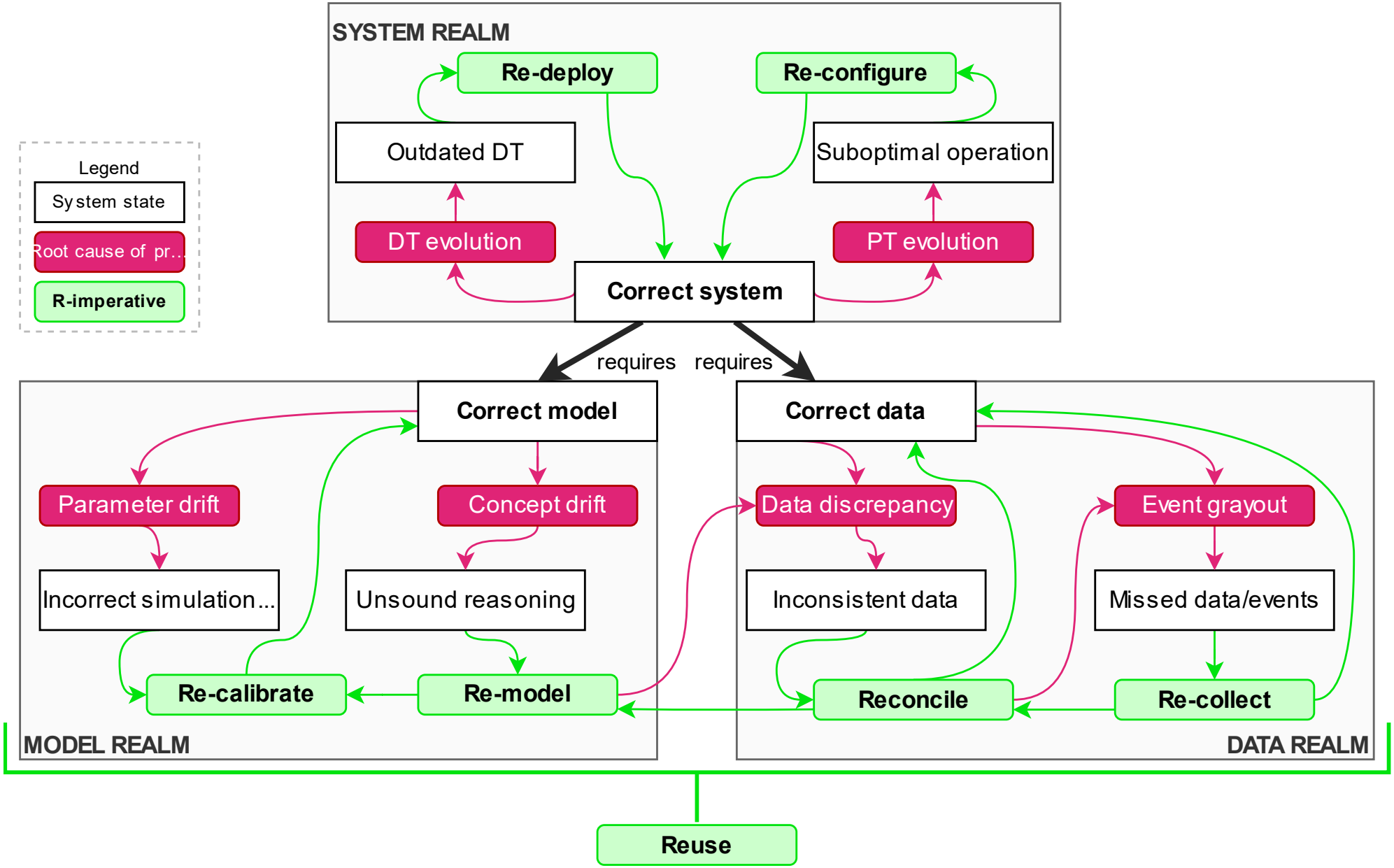
SPARSH MITTAL, Oak Ridge National Laboratory

Evolution of Digital Twins

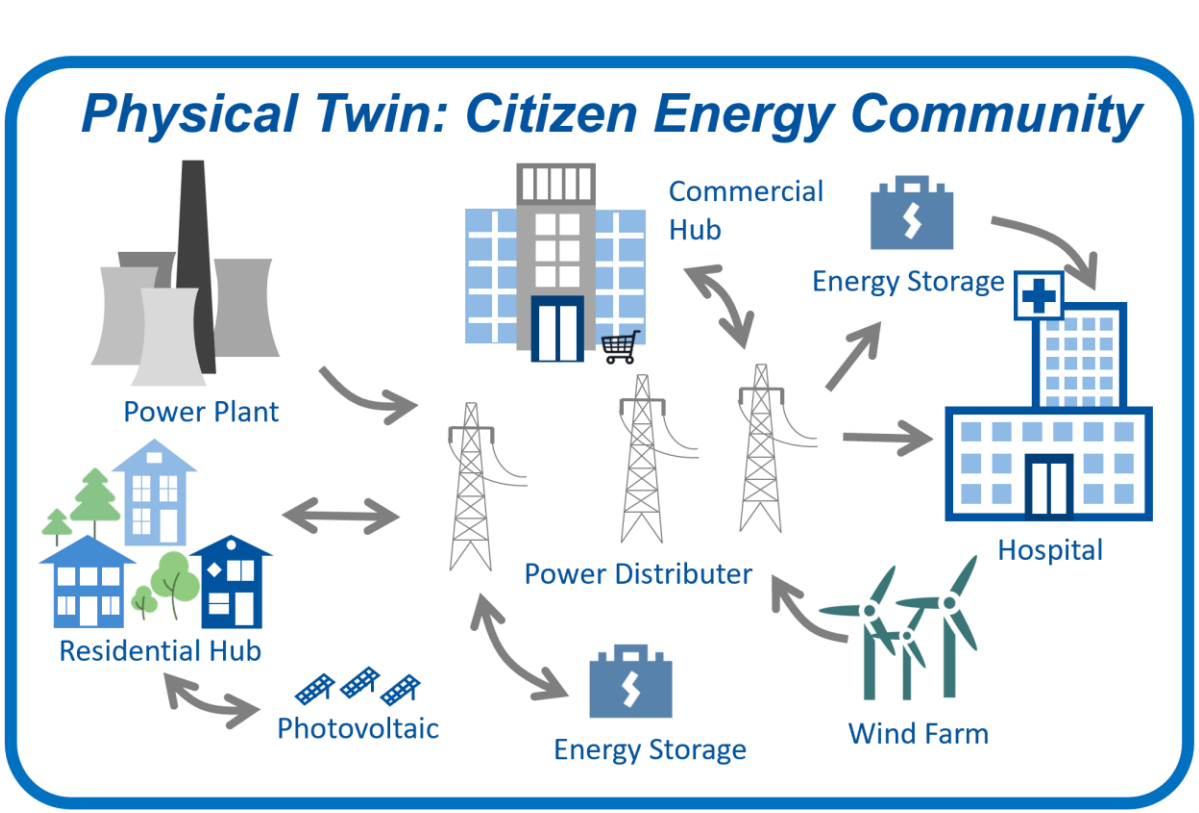


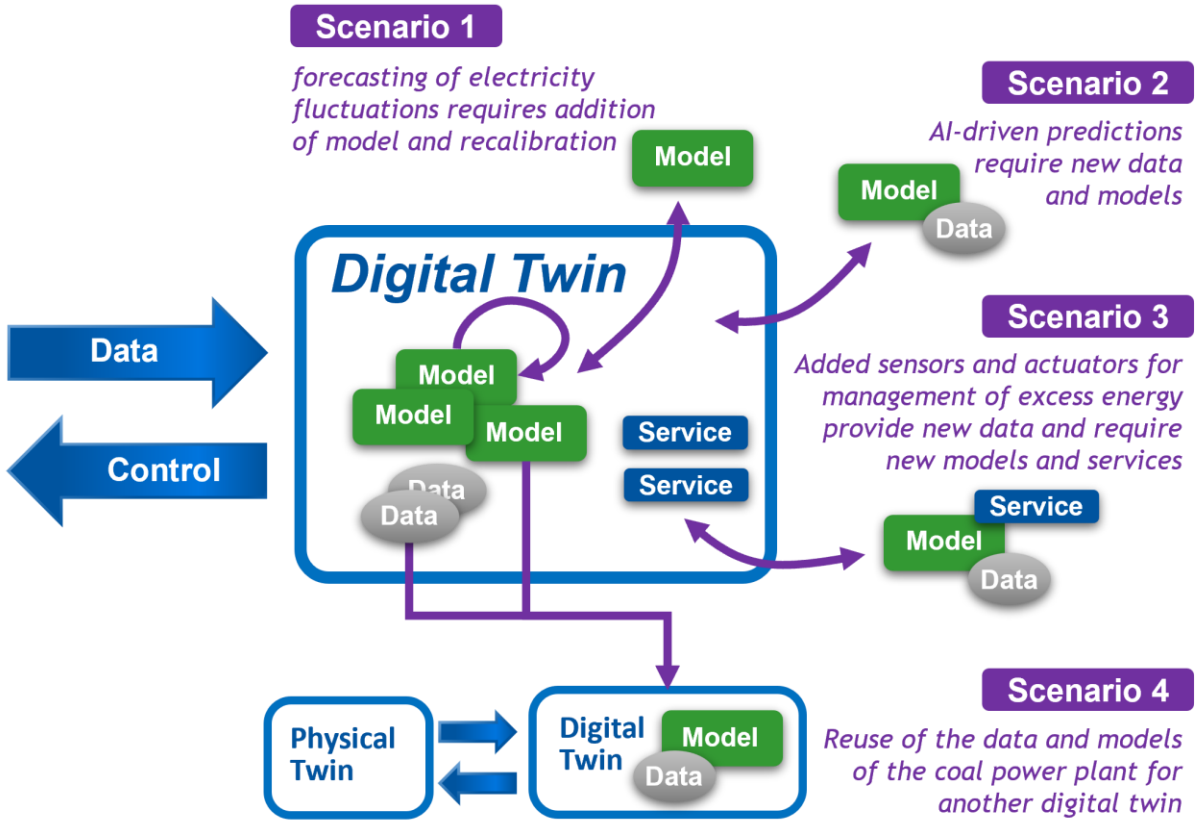
- Istvan David and Dominik Bork. "Towards a Taxonomy of Digital Twin Evolution for Technical Sustainability". In: MODELS-C 2023 Companion, Vasteras, Sweden. IEEE, 2023
- Judith Michael, Istvan David, and Dominik Bork. "Digital Twin Evolution for Sustainable Smart Ecosystems". In: MODELS-C 2024 Companion,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

Evolution of Digital Twins



Evolution of Digital Twins





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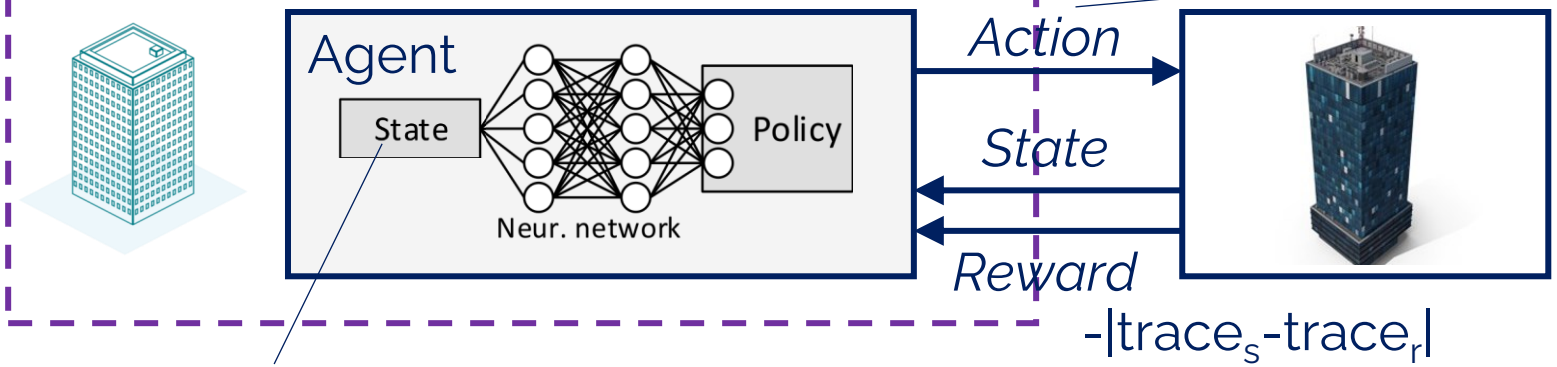
Rapid development of Digital Twins: Simulator inference by reinforcement learning

Digital Twin



a specific DEVS configuration
(structure and parameters)

State actions		
Add DEVS state	$addState(M,s) : M' = M \mid S \cup \{s\},\ ta(s) = \inf$	(8)
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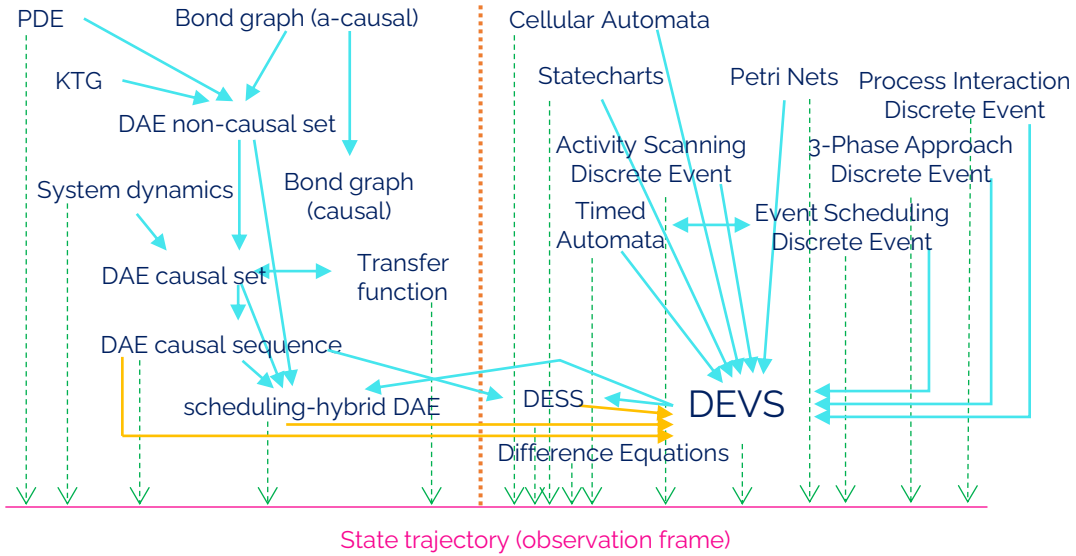


- Istvan David and Eugene Syriani. "Automated Inference of Simulators in Digital Twins". In: Handbook of Digital Twins. To appear. CRC Press, 2023. isbn: 978-1-032-54607-0
- Istvan David and Eugene Syriani. "DEVS Model Construction as a Reinforcement Learning Problem". In: 2022 Annual Modeling and Simulation 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

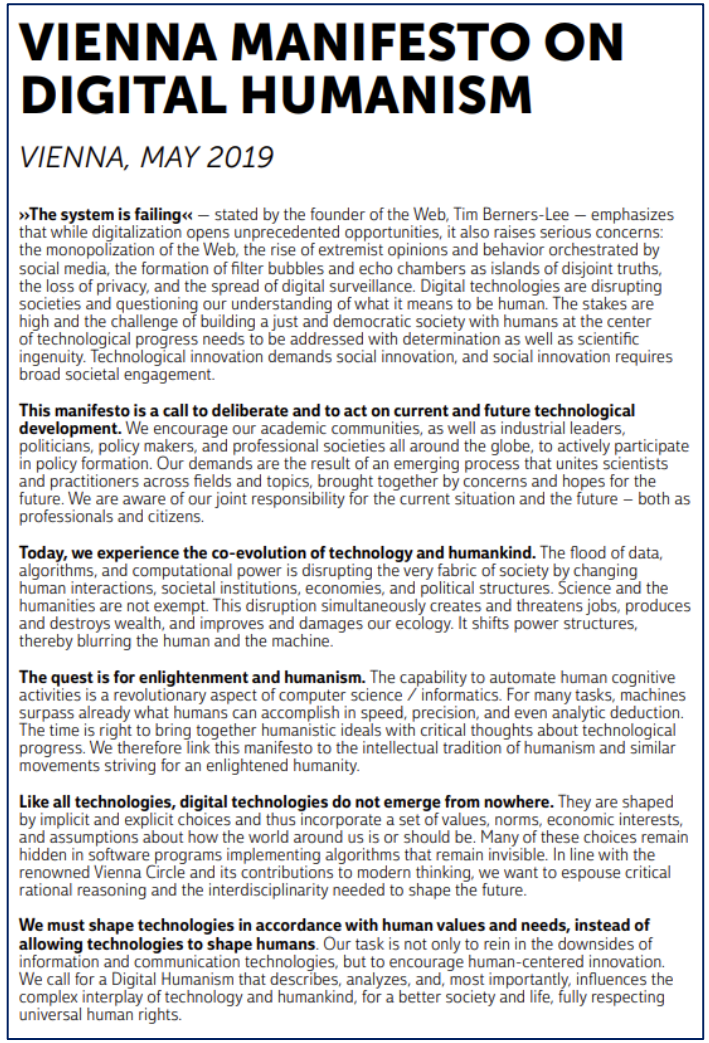
Adoption in lower-income economies?

- 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.

Tzachor, A., Sabri, S., Richards, C.E. *et al.* Potential and limitations of digital twins to achieve the Sustainable Development Goals. *Nat Sustain* **5**, 822–829 (2022). https://doi.org/10.1038/s41893-022-00923-7

Twin transition

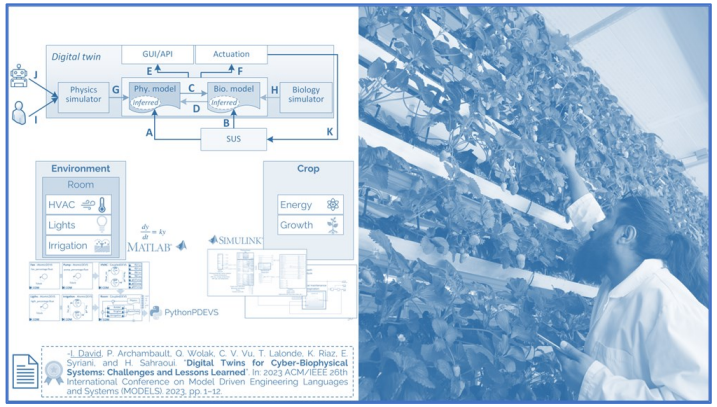
Top Strategic Technology Trends 2024

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

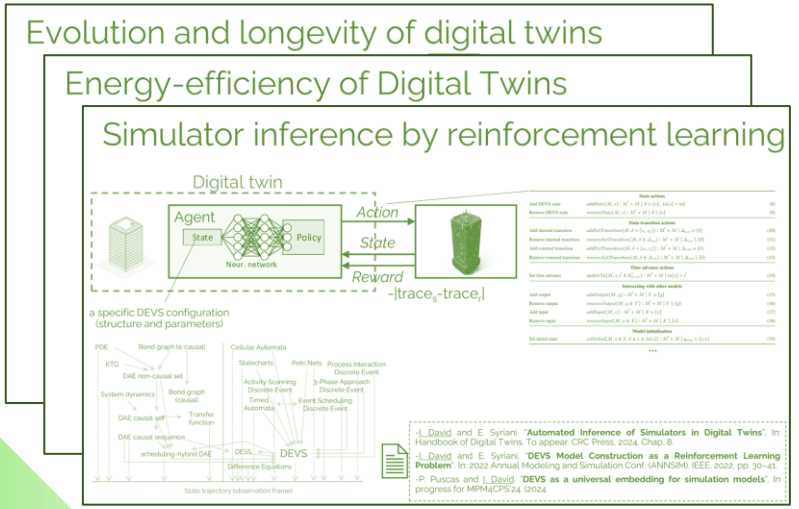
Source: Gartner

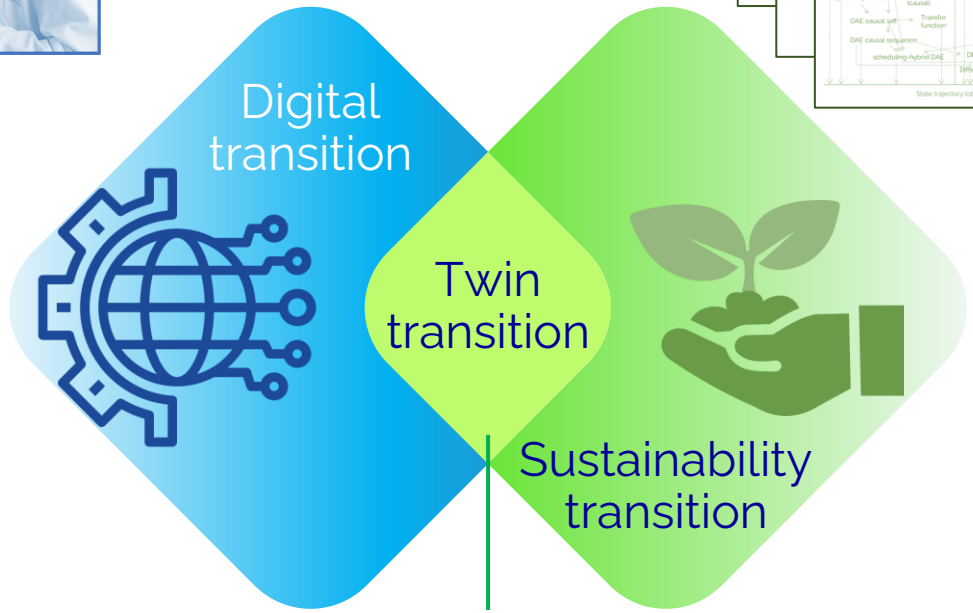
Gartner

Sustainable systems



...by sustainable methods





Sustainability *of and by* digital tech

Sustainable Systems and Methods

Baran Shajari

McMaster University

By way of conclusion

Digital Twins
Foundations and applications