McMaster University

ENGINEERING
Computing & Software

Sustainable Systems and Methods

Centre for Software Certification (McSCert)

Engineering complex and sustainable systems through digital twins

Prof. Istvan David
Faculty of Engineering
McMaster University, Canada

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istvandavid.com

March 14, 2025

POLYTECHNIQUE MONTRÉAL
UNIVERSITÉ D'INGÉNIERIE

Dr. Istvan David

Sustainable Systems and Methods

ENGINEERING Computing & Software

McMaster University

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

modeling and simulation
engineering processes
PhD in Computer Science (2014–19)
University of Antwerp, Belgium

IVADO Postdoctoral Laureate 2021
digital twins for C(B)PS
reinforcement learning
Postdoctoral researcher (2021–2023)
Université de Montréal, Canada

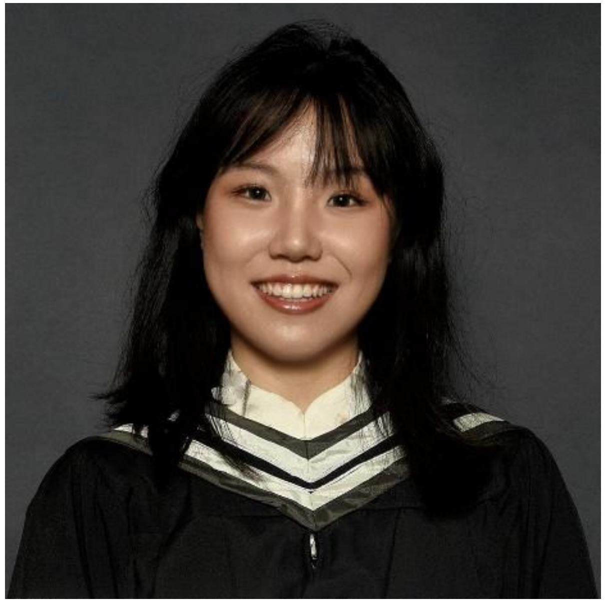
digital twins and sustainability
energy-aware systems
Assistant Professor (2023–)
McMaster University, Canada

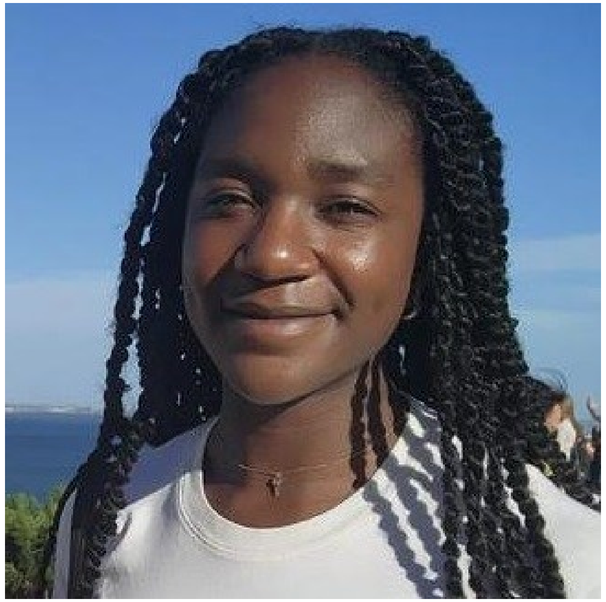
R&D Software Engineer (2012–2014)
Mentor Graphics, Hungary

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

Sustainable Systems and Methods

https://istvandavid.com/team





Sustainable Systems and Methods

https://istvandavid.com/lab

*Sustainable systems **by** sustainable methods*

Sustainability

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

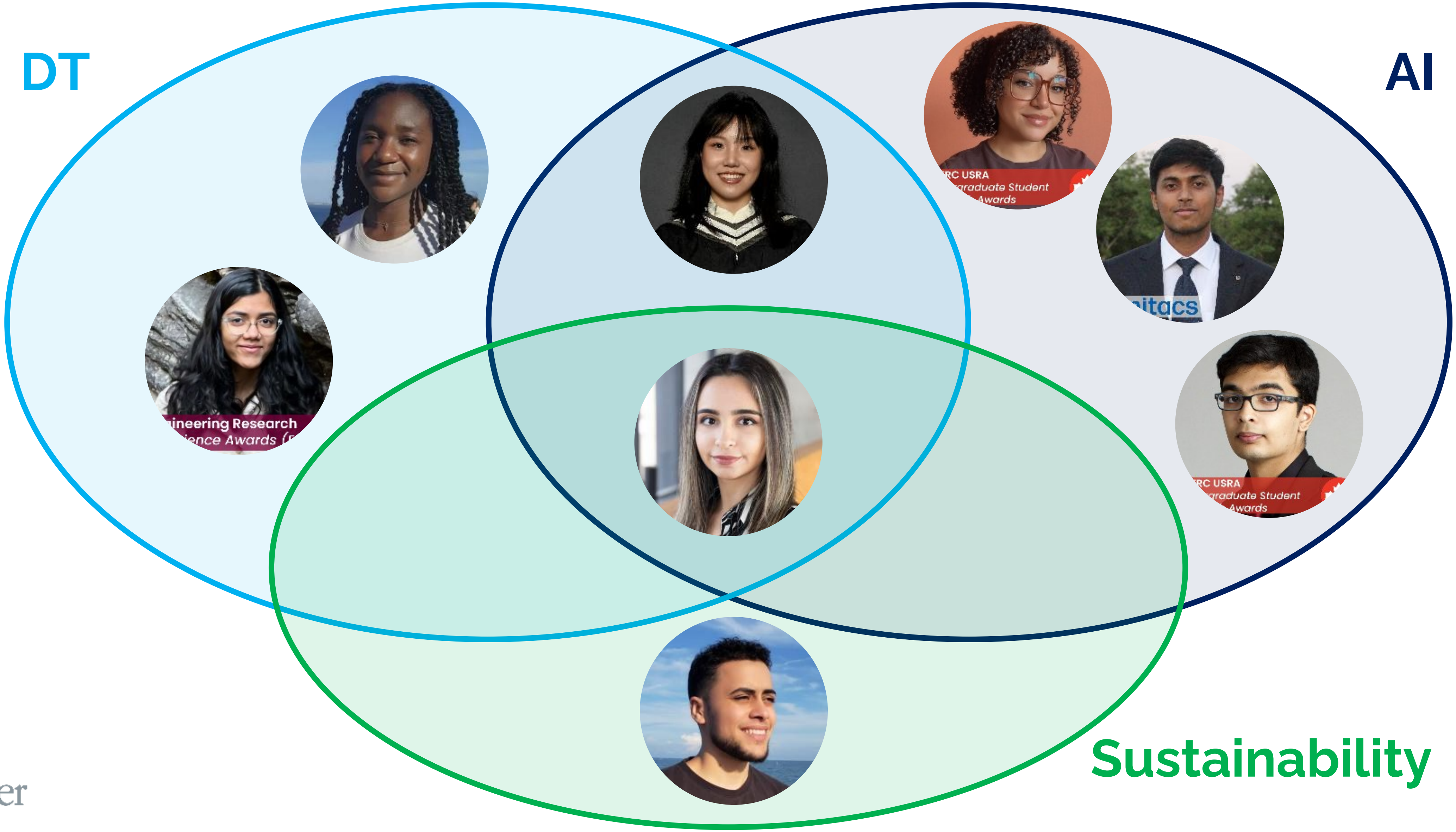
Digitalization

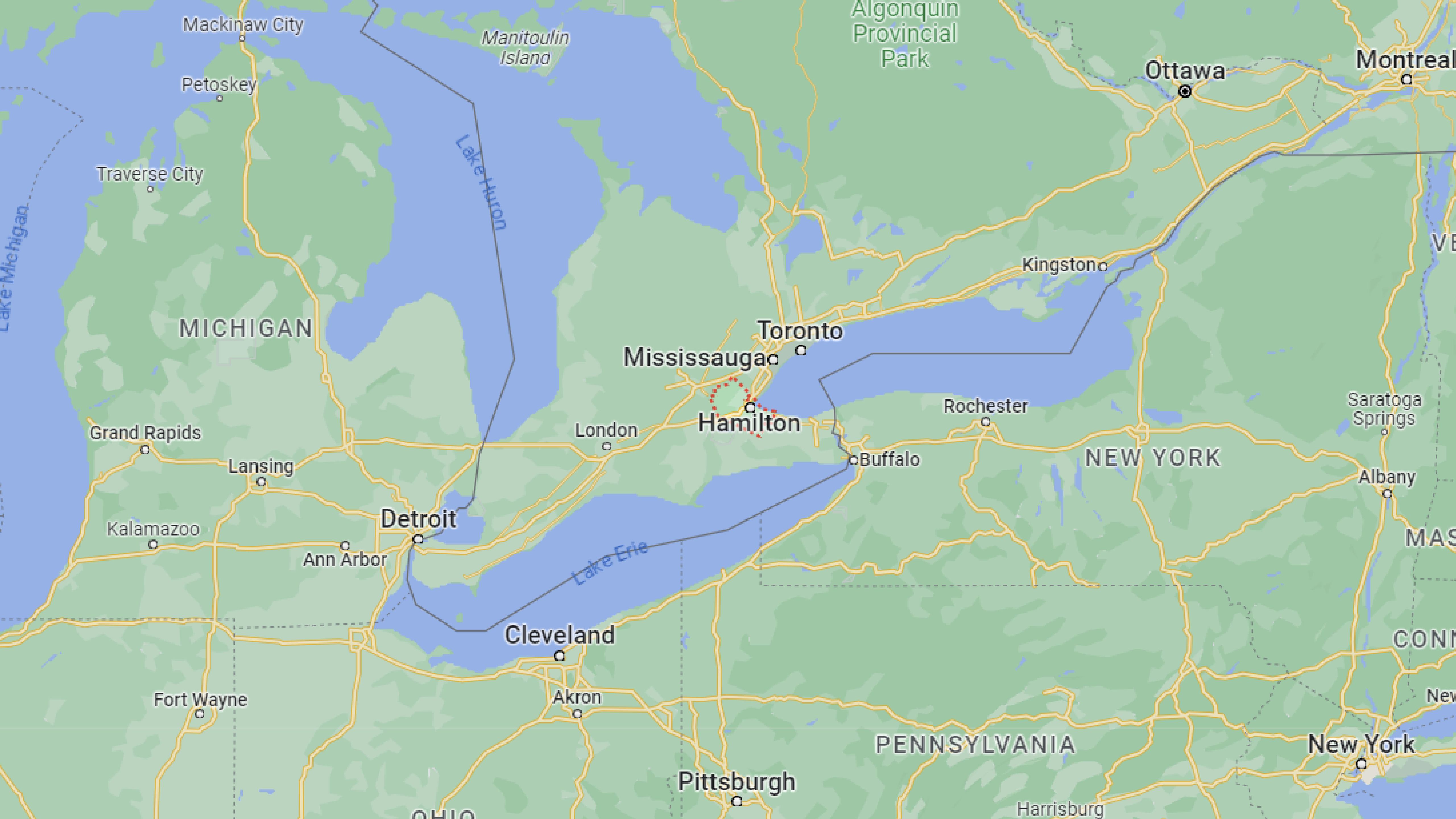
- Digital twins
- Digital thread
- Machine learning / AI
- Tool chains and process tools

Modeling & Simulation

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

Sustainable Systems and Methods

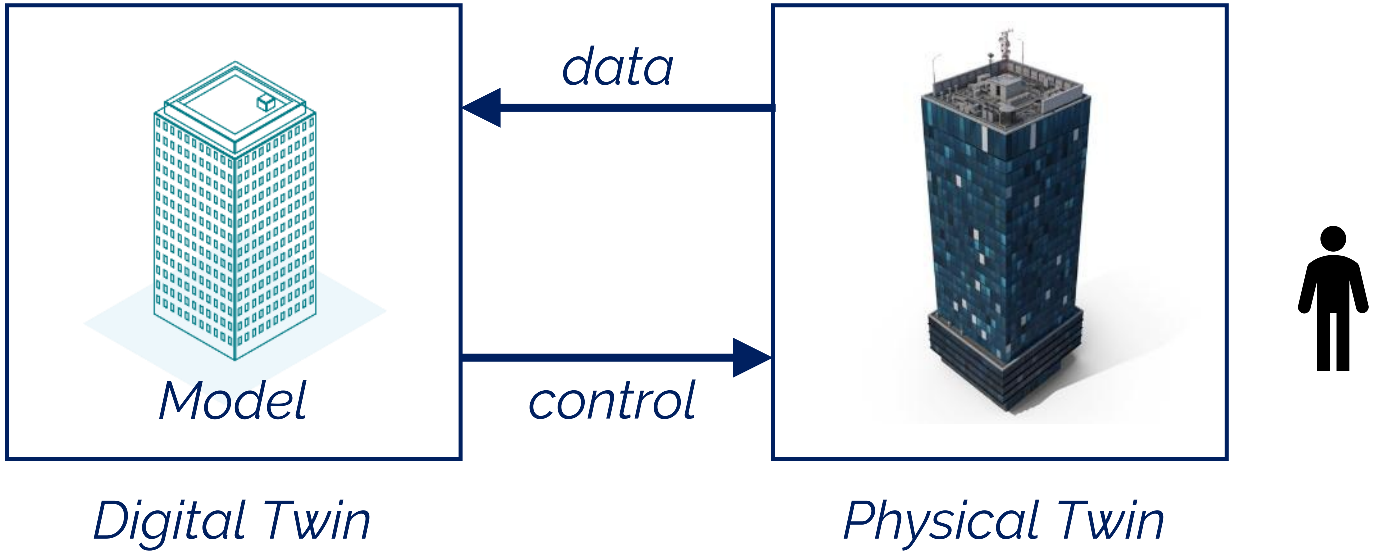



Mackinaw City
Manitoulin Island
Algonquin Provincial Park
Ottawa
Montreal
Petoskey
Lake Huron
Traverse City
Lake Michigan
Kingston
MICHIGAN
Toronto
Mississauga
Hamilton
Rochester
Saratoga Springs
Grand Rapids
London
Buffalo
NEW YORK
Lansing
Albany
Detroit
Kalamazoo
Ann Arbor
Lake Erie
Cleveland
Akron
Fort Wayne
PENNSYLVANIA
New York
Pittsburgh
Harrisburg

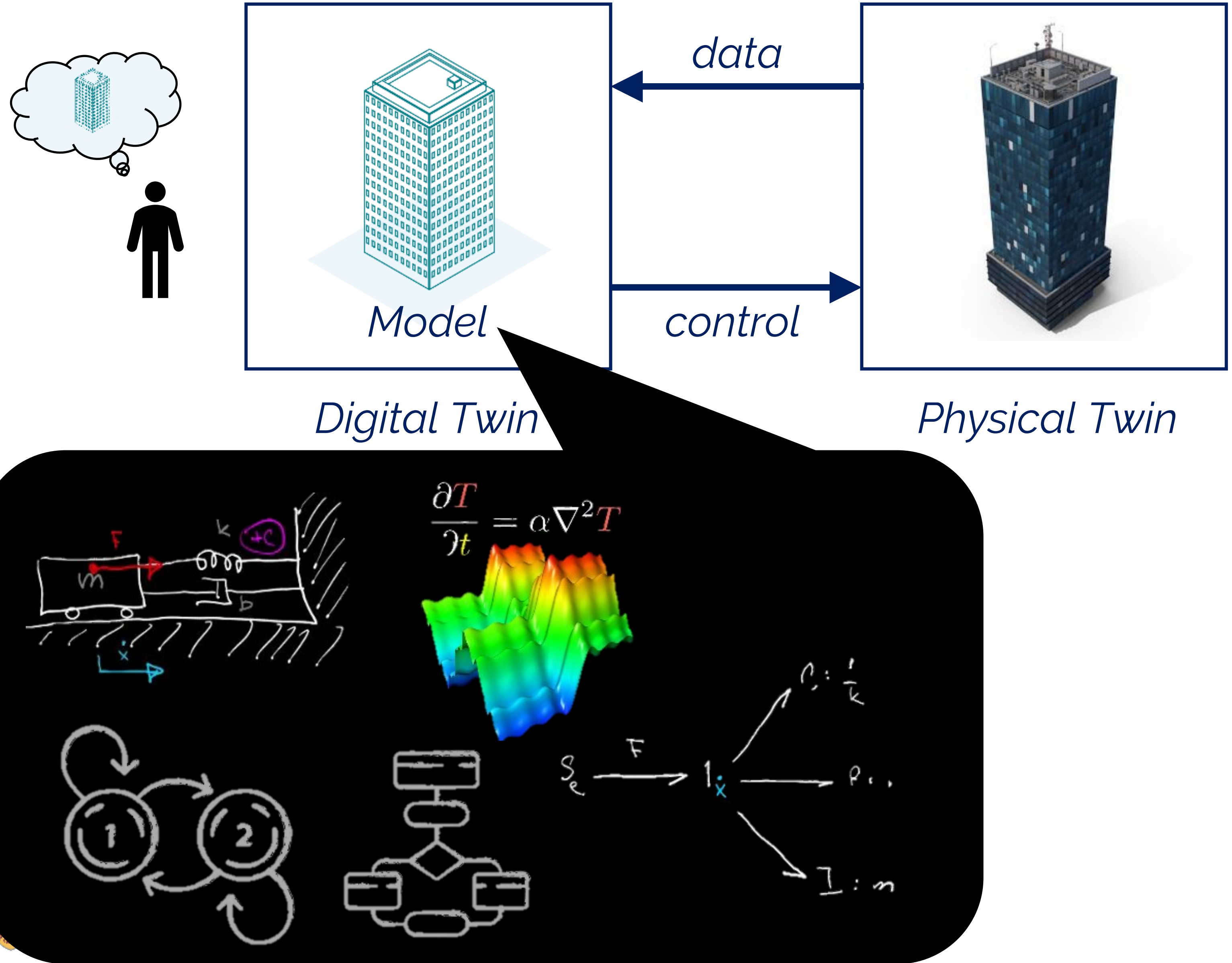
McMaster University
Newmarket
Richmond Hill
Vaughan
Markham
Oshawa
Brampton
Toronto
Mississauga
Milton
Oakville
Listowel
Guelph
Kitchener
Stratford
Cambridge
St. Marys
Hamilton
Niagara-on-the-Lake
St. Catharines
Lockport
Niagara Falls
Ingersoll
Welland
Amherst
Tillsonburg
Simcoe
Buffalo

Ye olde digital twin

A fit-for-purpose definition of “digital twin”



A fit-for-purpose definition of "digital twin"

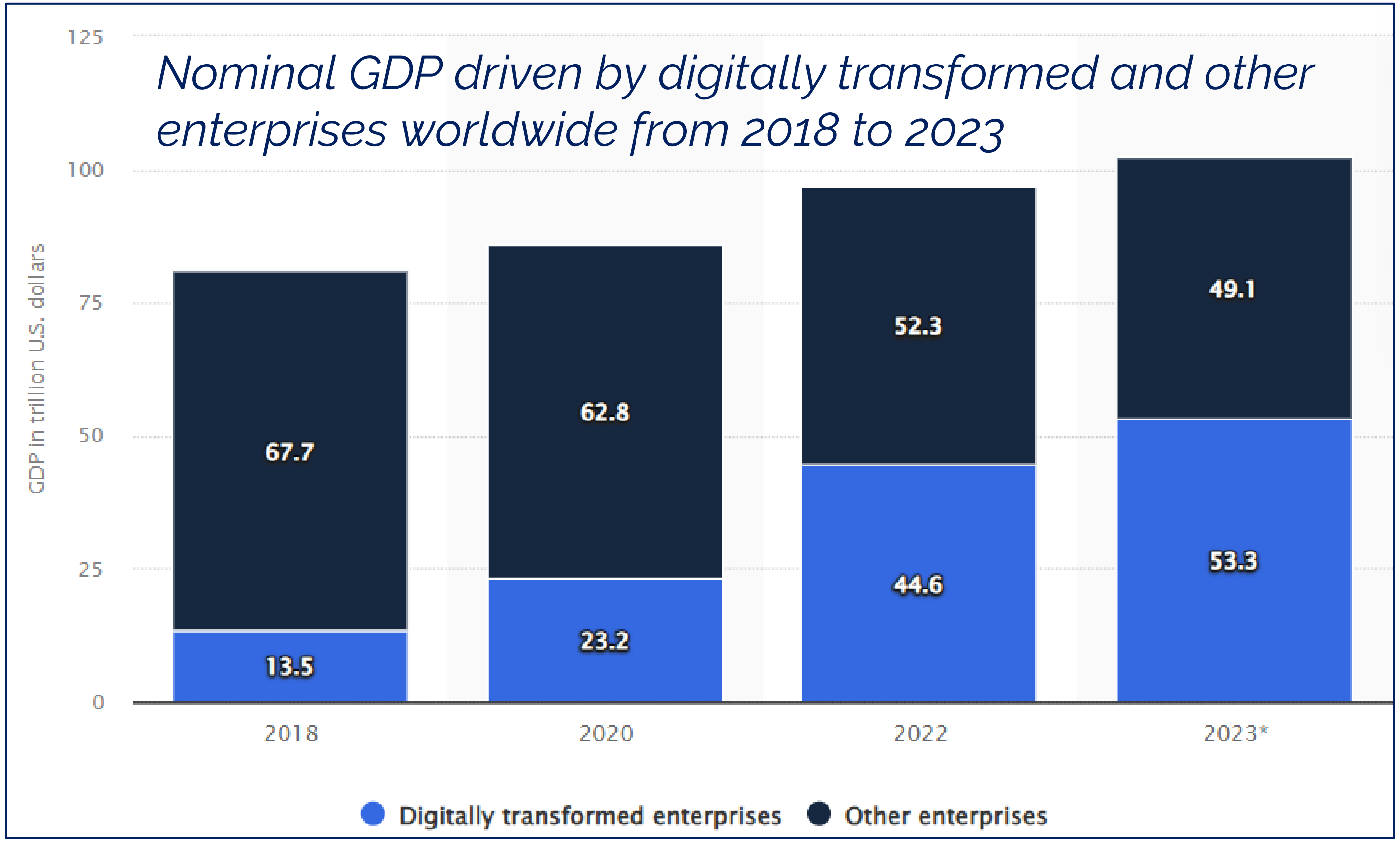


Digitalization and digital transformation

Industry 4.0 and 5.0

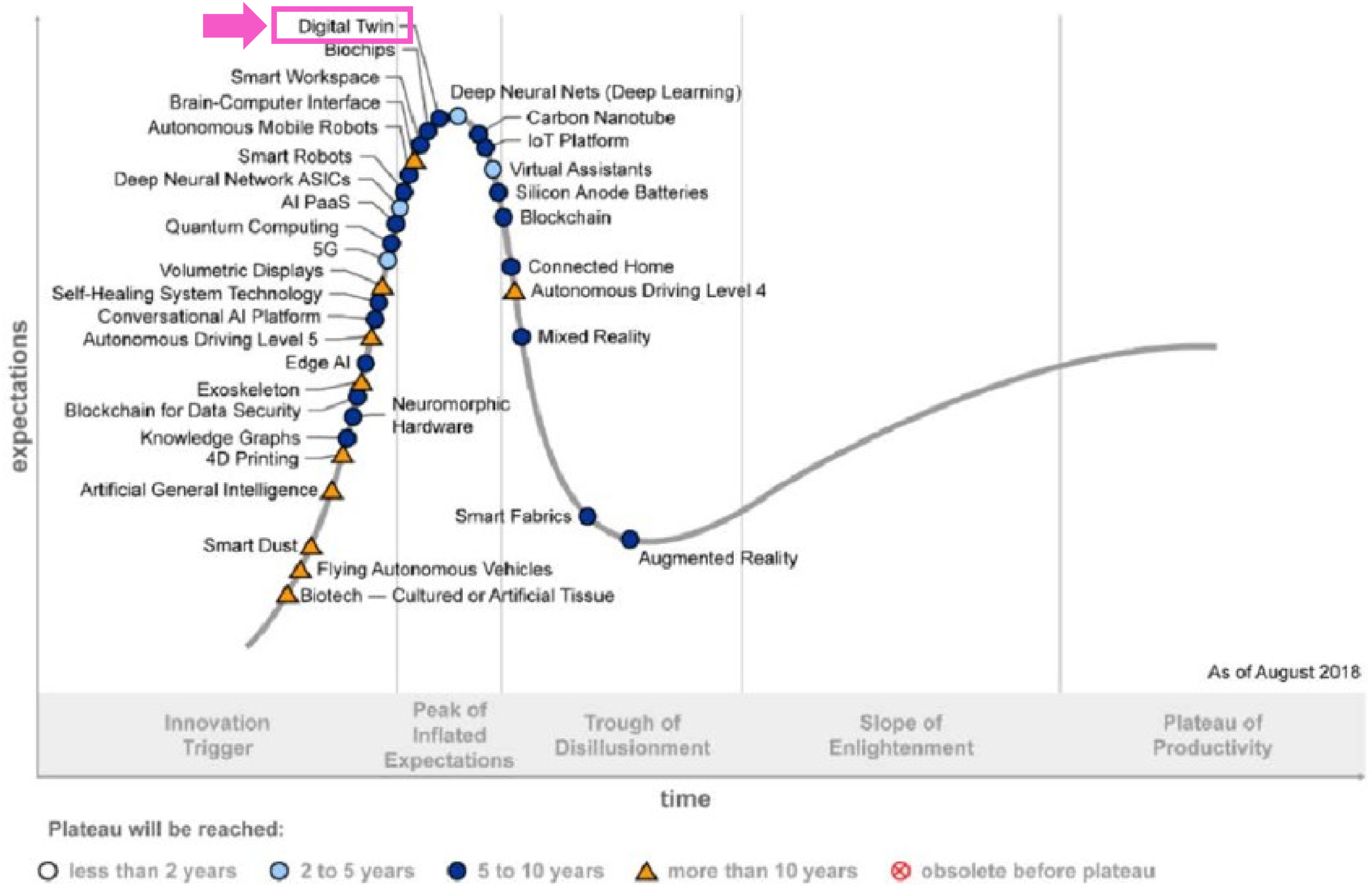
I5.0 complements the existing I4.0 approach by specifically putting research and innovation at the service of the transition to a **sustainable, human-centric** and **resilient European industry**

European Commission



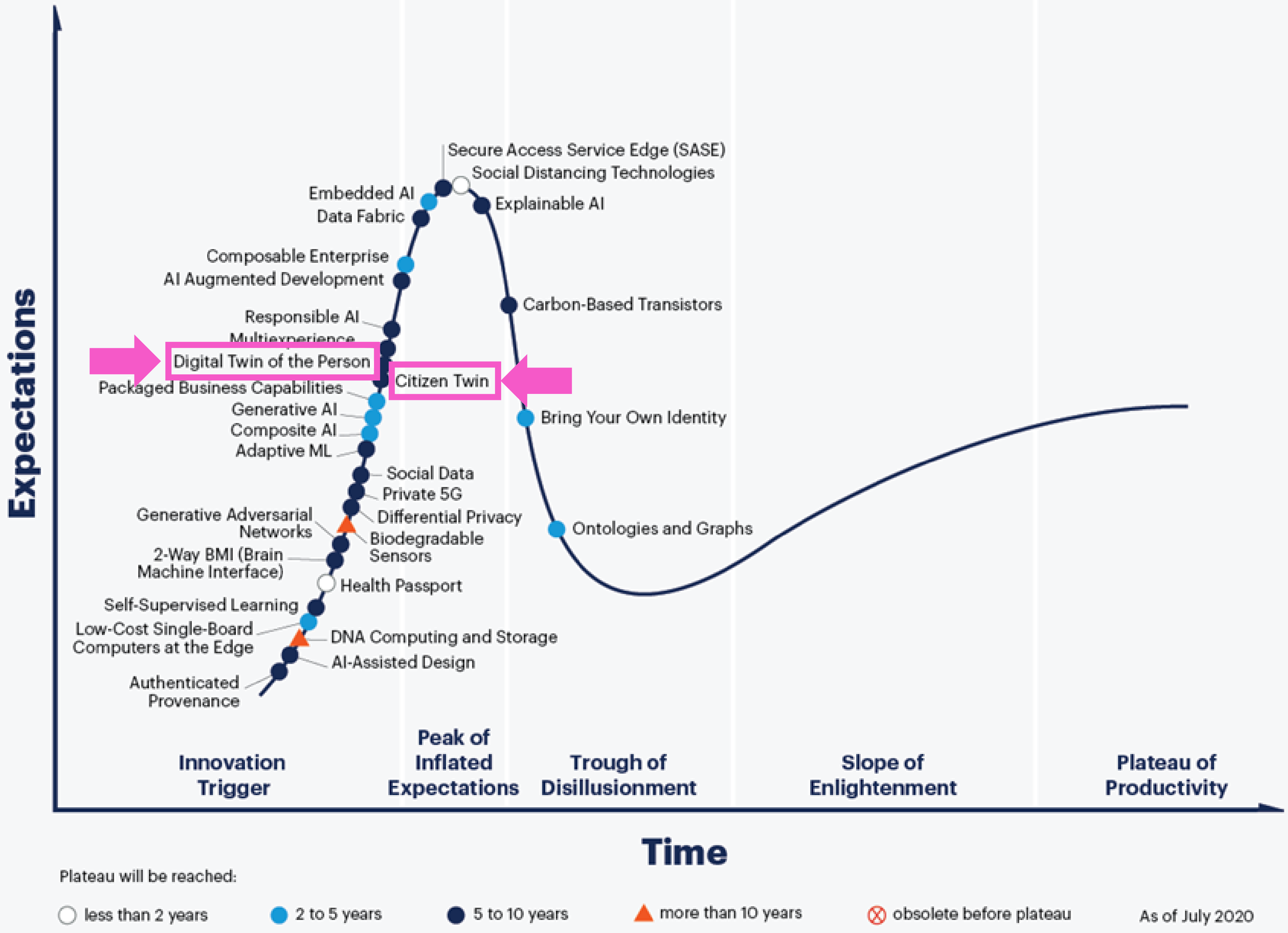
https://www.statista.com/statistics/1134766/nominal-gdp-driven-by-digitally-transformed-enterprises/

2018

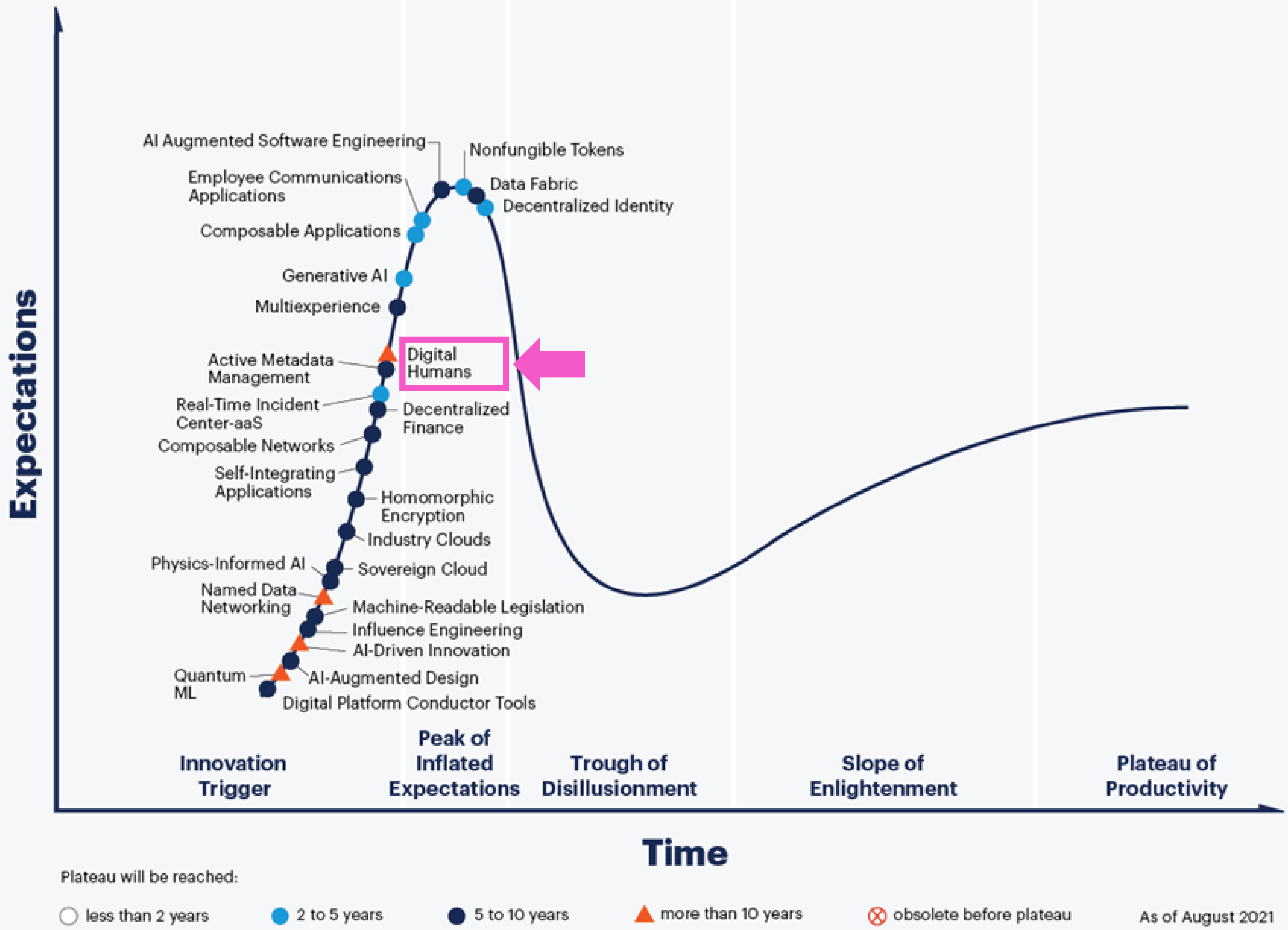

Digital Twin
Biochips
Smart Workspace
Brain-Computer Interface
Autonomous Mobile Robots
Smart Robots
Deep Neural Network ASICs
AI PaaS
Quantum Computing
5G
Volumetric Displays
Self-Healing System Technology
Conversational AI Platform
Autonomous Driving Level 5
Edge AI
Exoskeleton
Blockchain for Data Security
Knowledge Graphs
4D Printing
Artificial General Intelligence
Smart Dust
Flying Autonomous Vehicles
Biotech — Cultured or Artificial Tissue
Neuromorphic Hardware
Deep Neural Nets (Deep Learning)
Carbon Nanotube
IoT Platform
Virtual Assistants
Silicon Anode Batteries
Blockchain
Connected Home
Autonomous Driving Level 4
Mixed Reality
Smart Fabrics
Augmented Reality
expectations
As of August 2018
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

Gartner Hype Cycle for Emerging Technologies, 2019

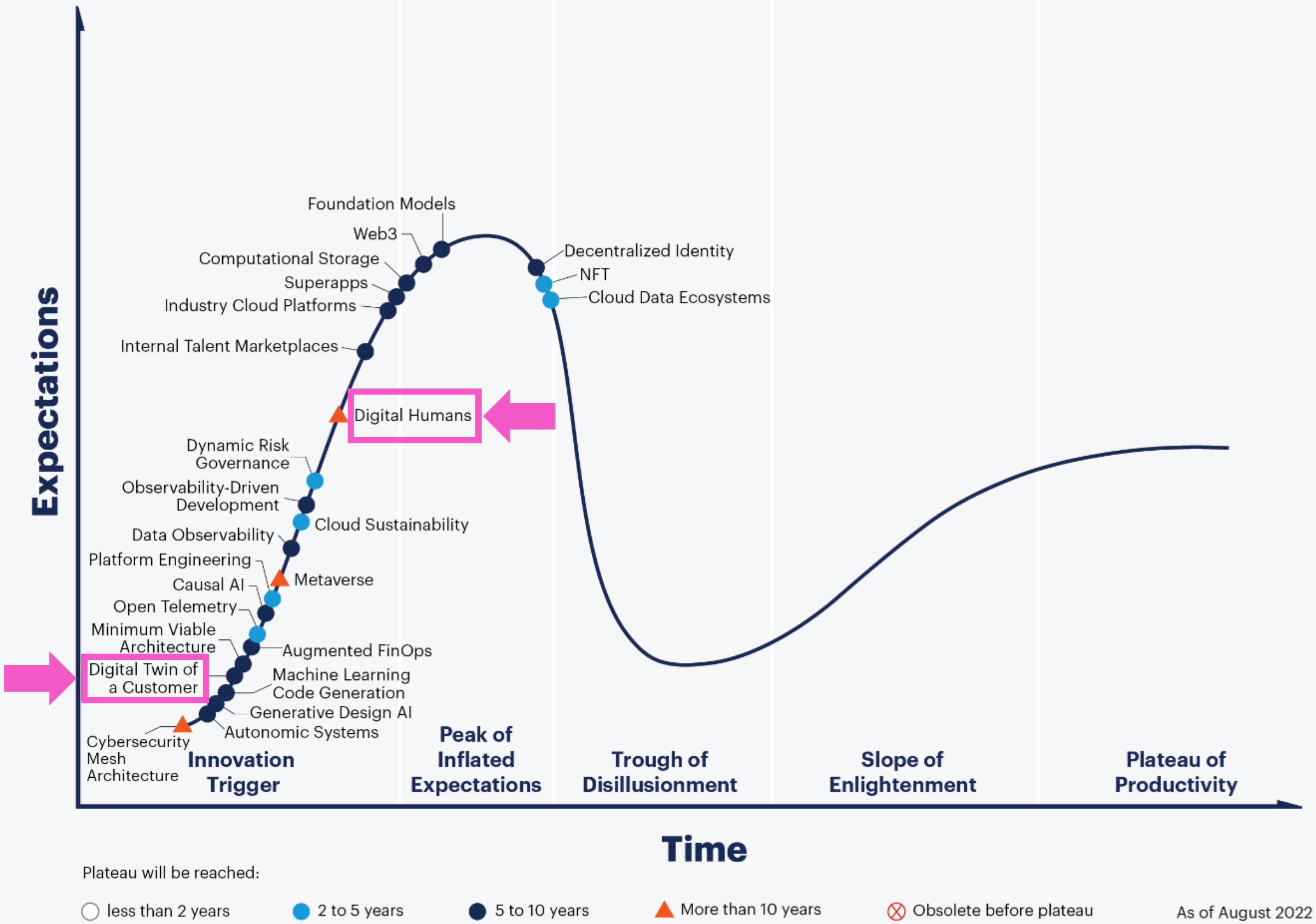
Hype Cycle for Emerging Technologies, 2020

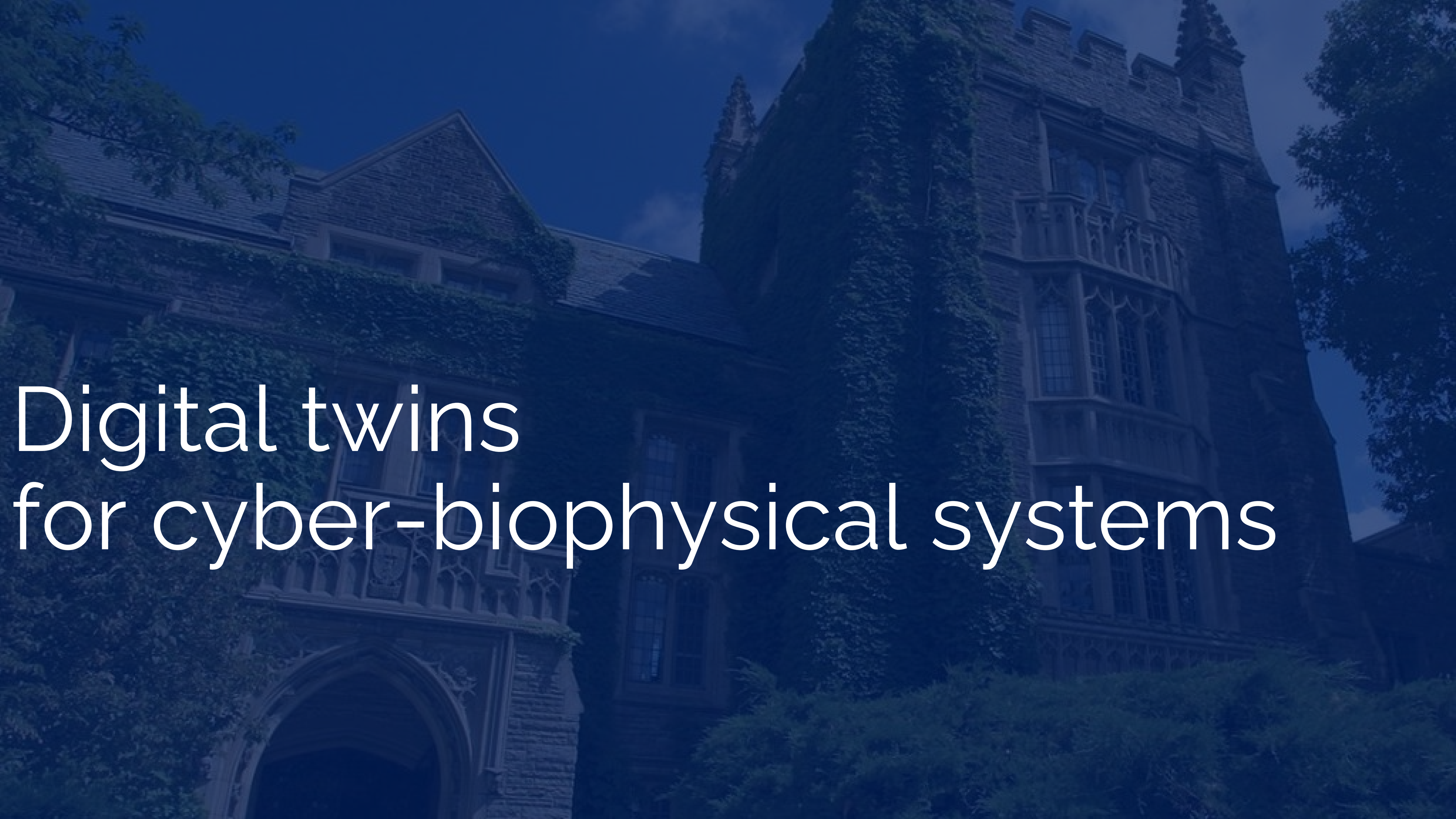


Hype Cycle for Emerging Technologies, 2021



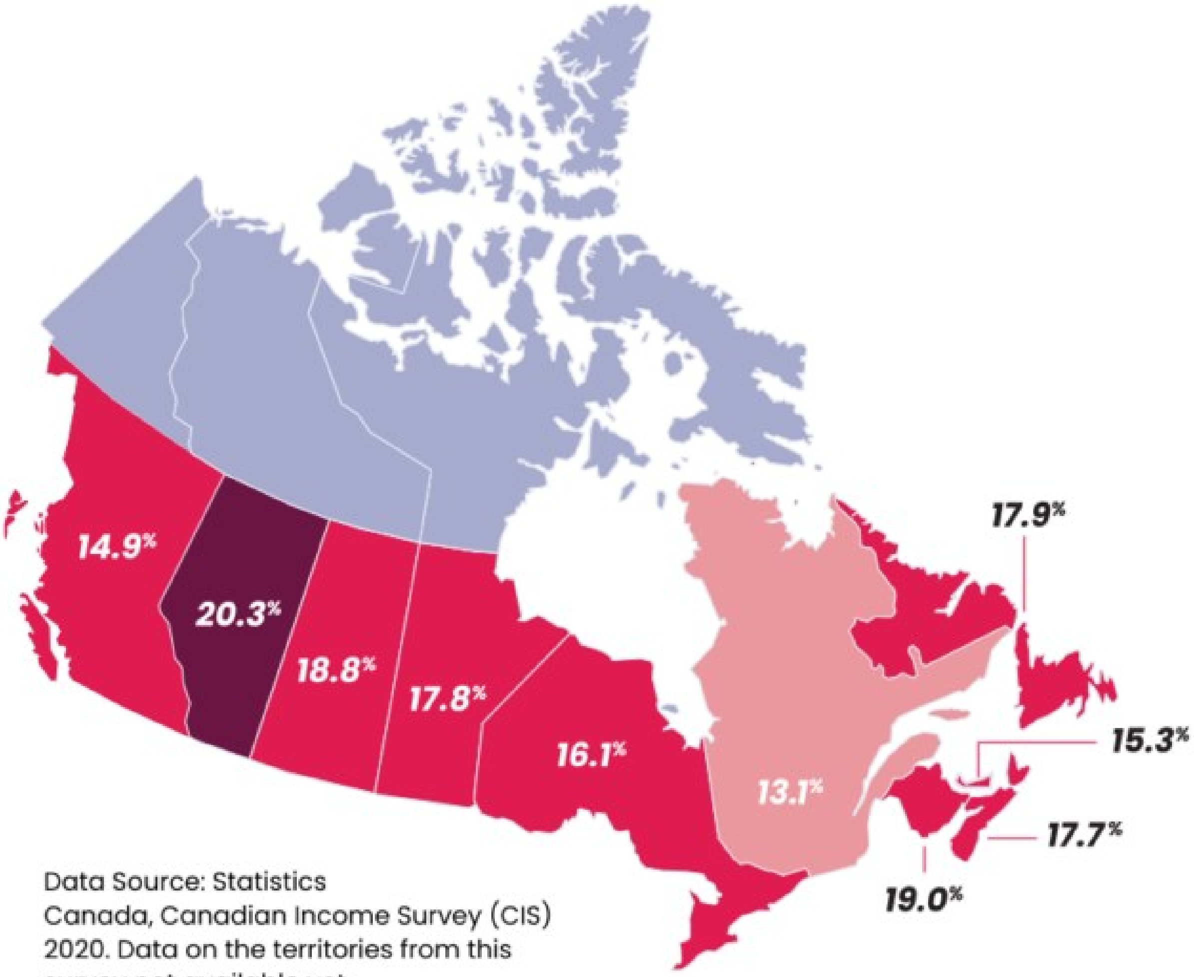
Hype Cycle for Emerging Tech, 2022





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.

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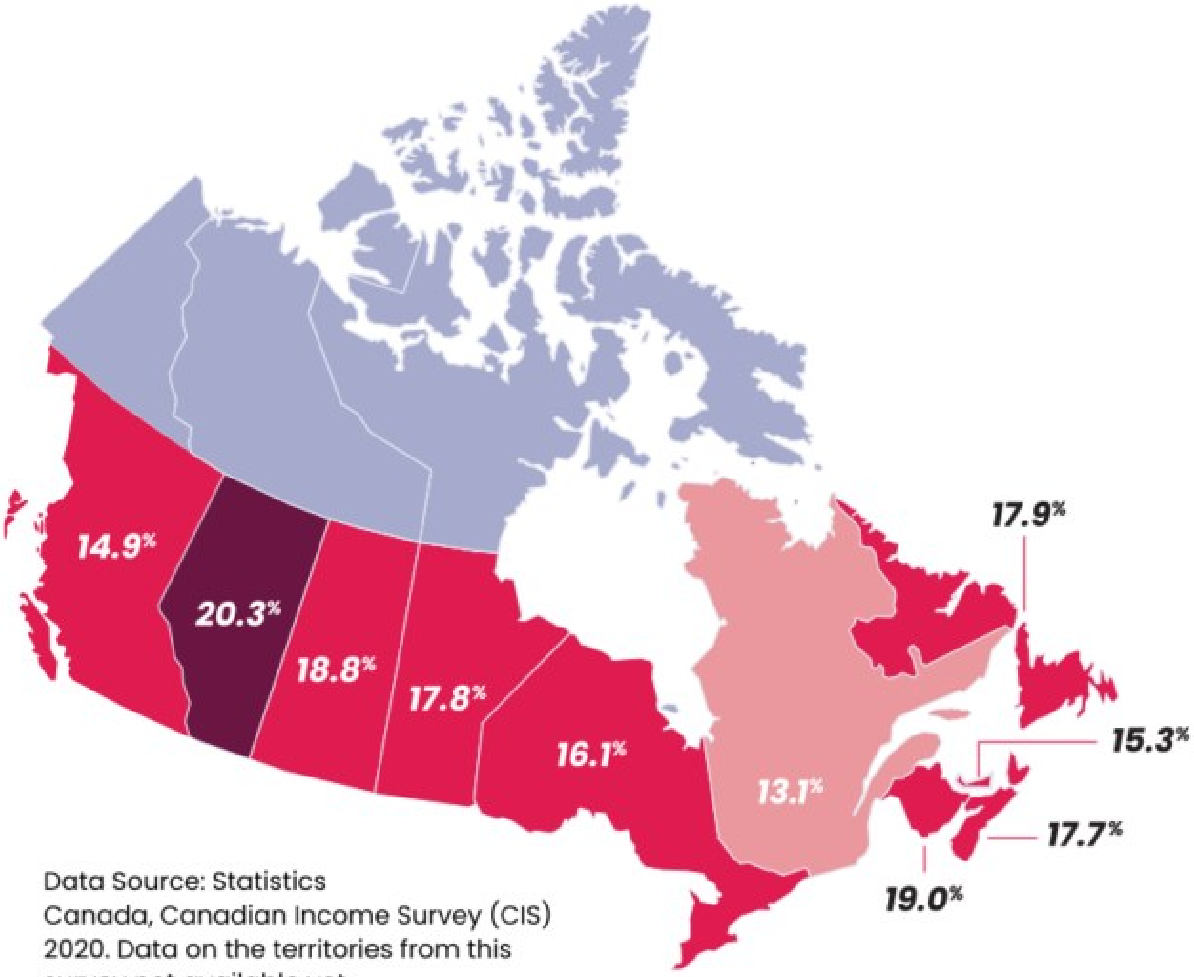
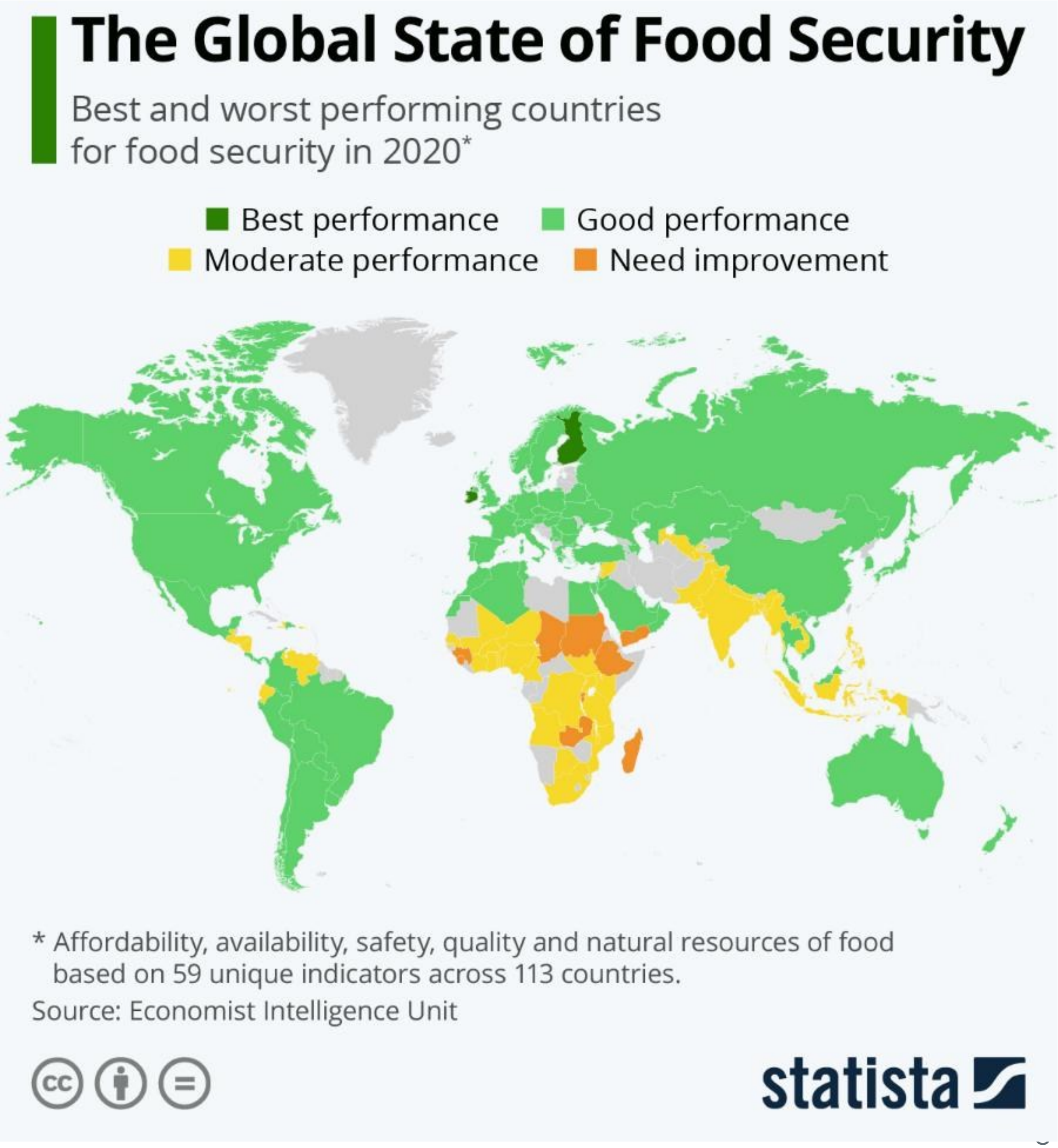
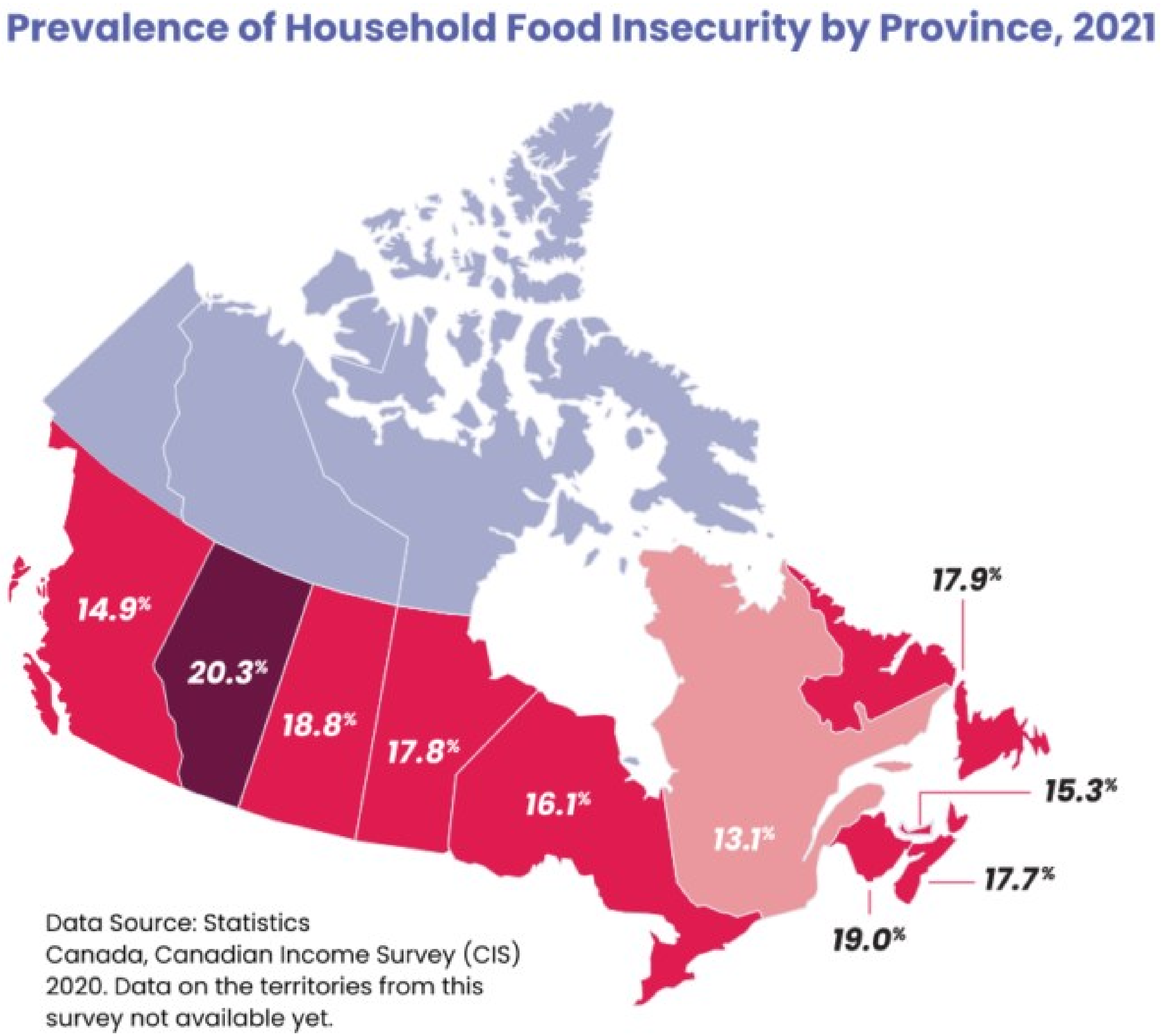
Prevalence of Household Food Insecurity by Province, 2021



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





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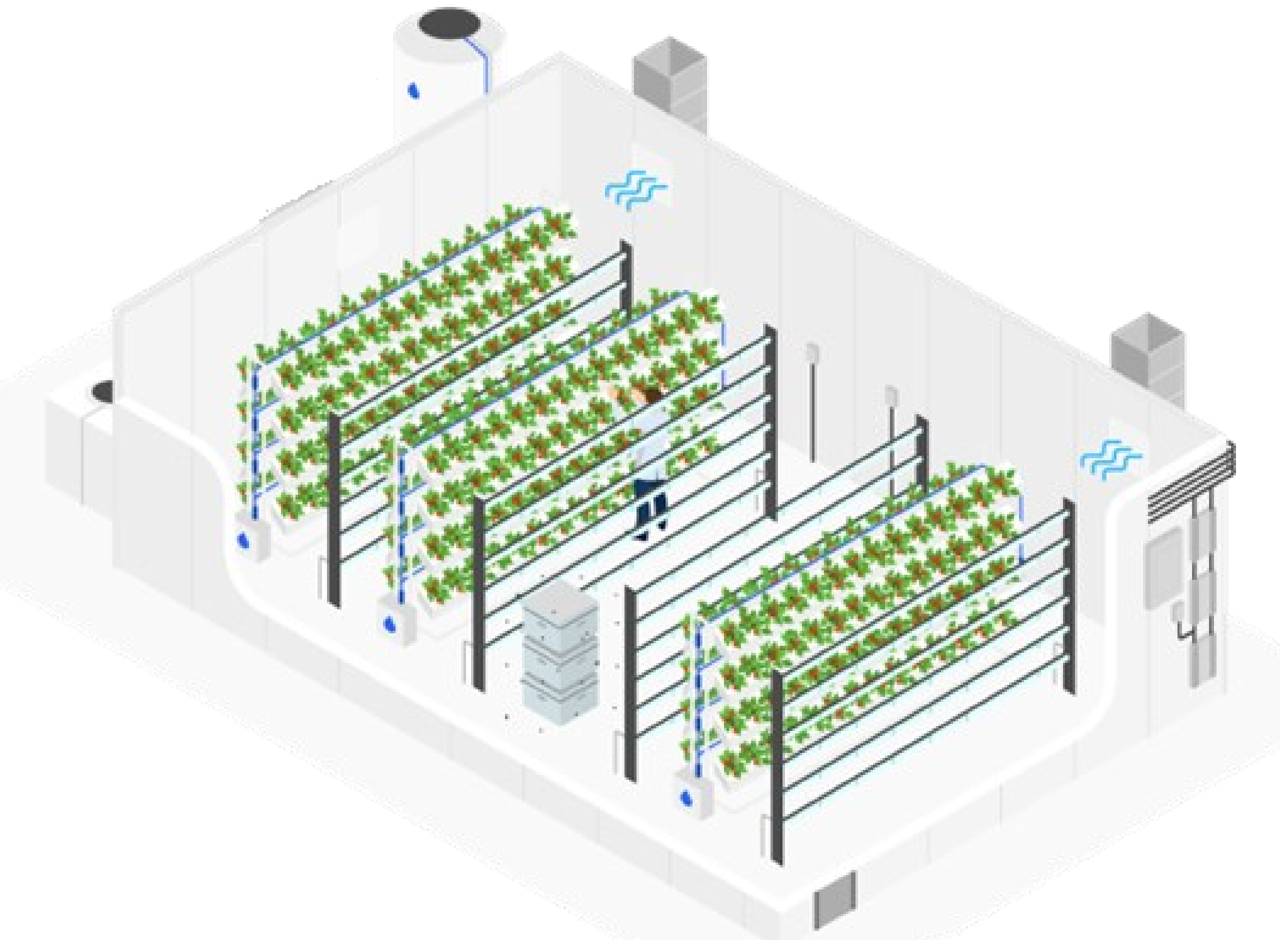
Controlled Environment Agriculture (CEA)



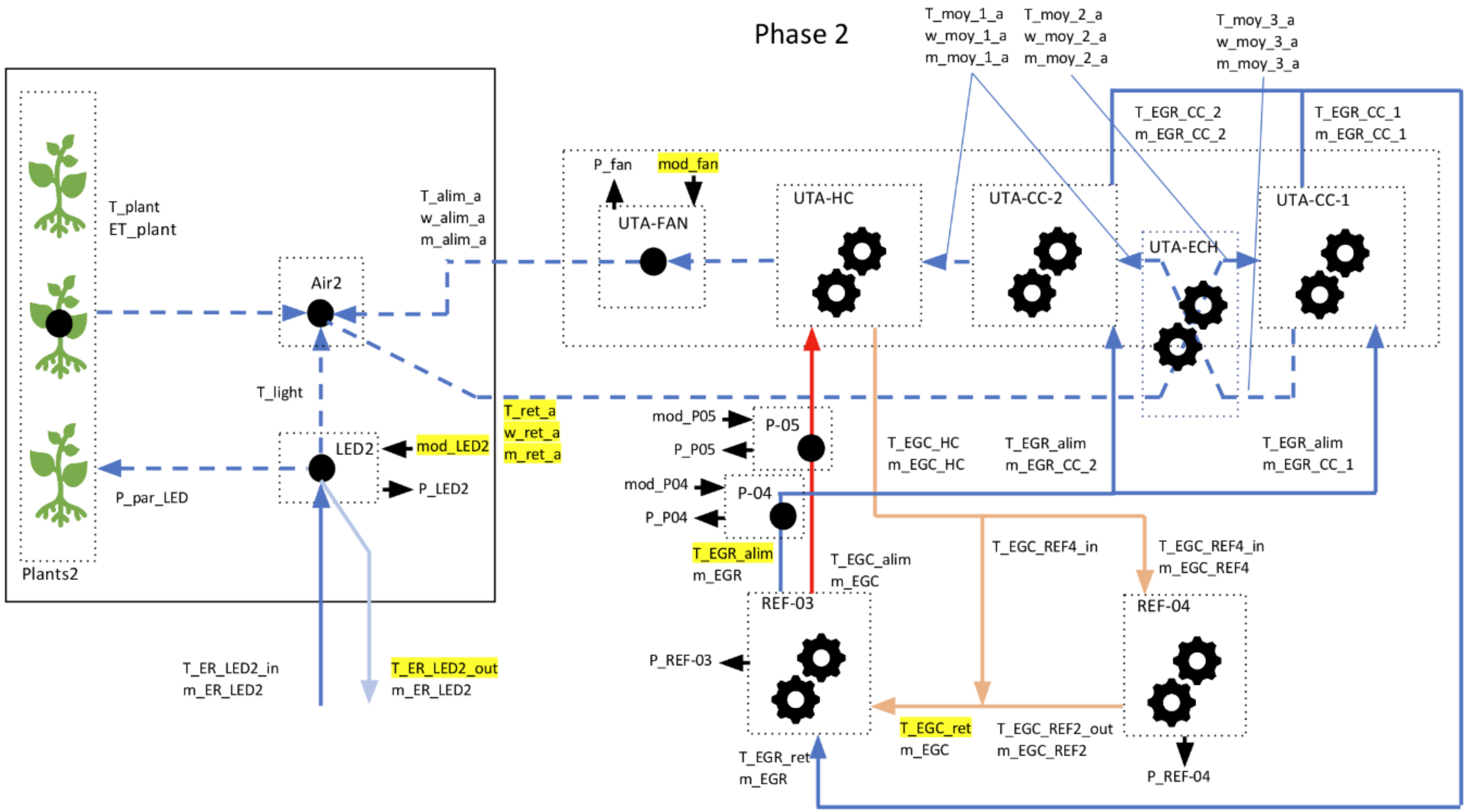
The challenge of CEA: **control is hard**

Maximize crop-to-energy ratio
Reduce waste

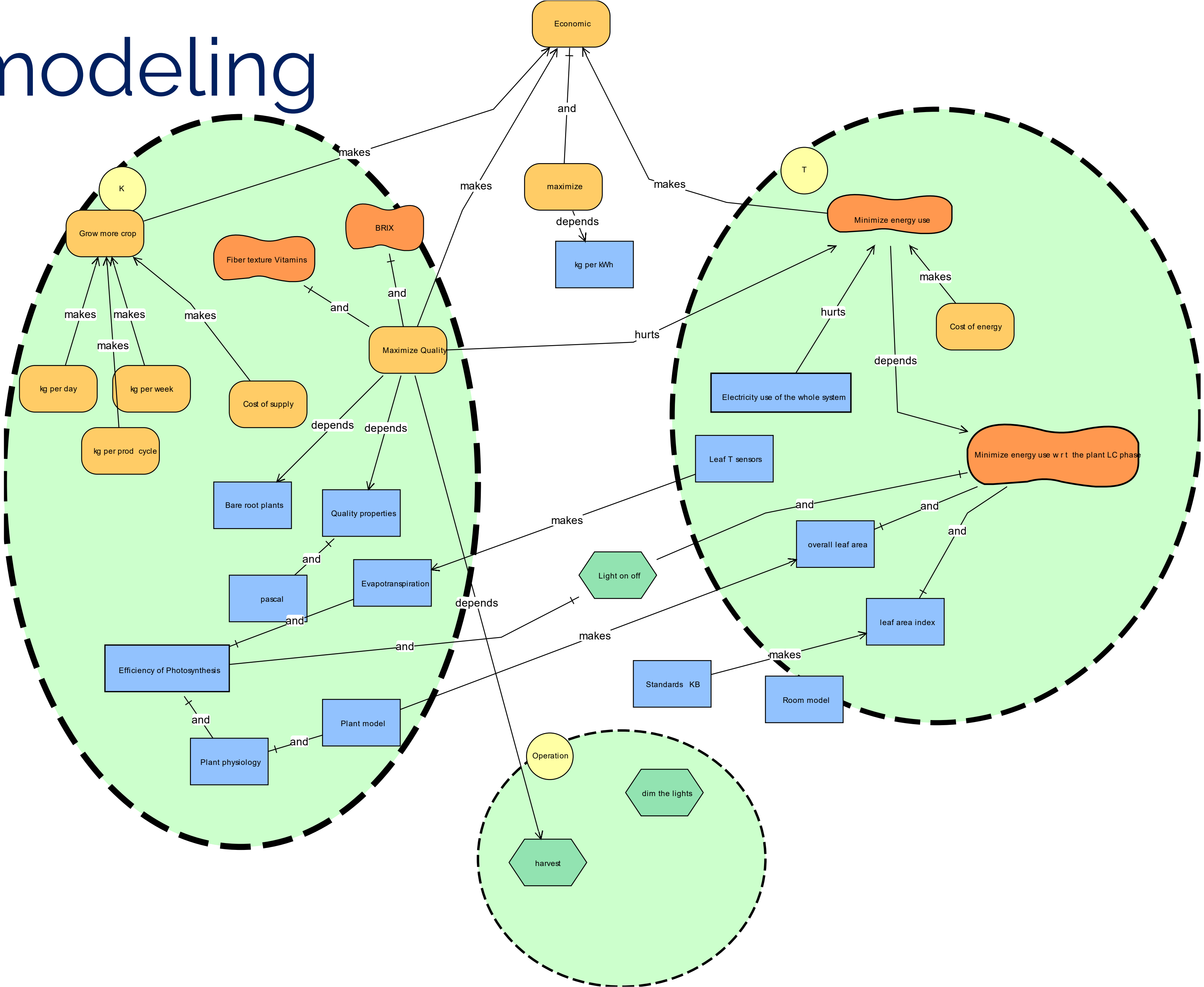
…

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

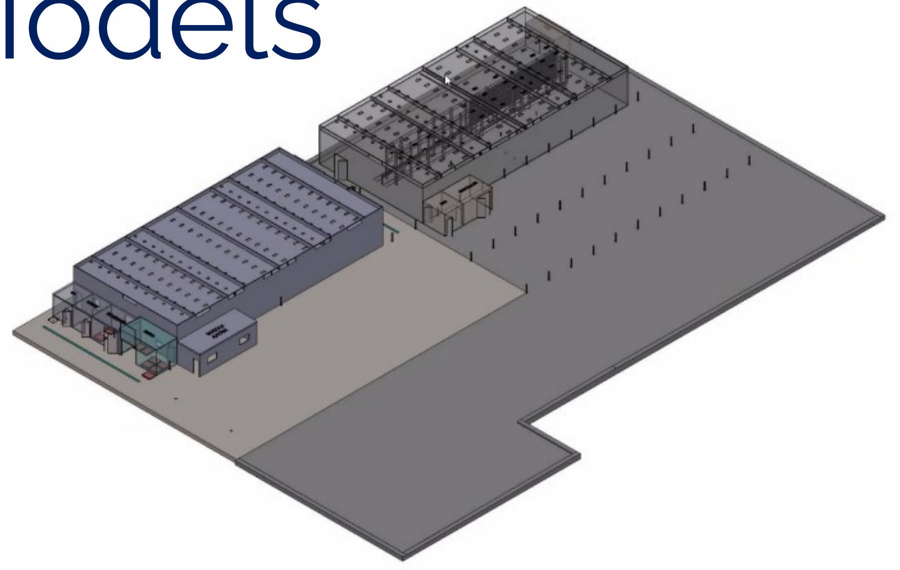
Expressing expert processes

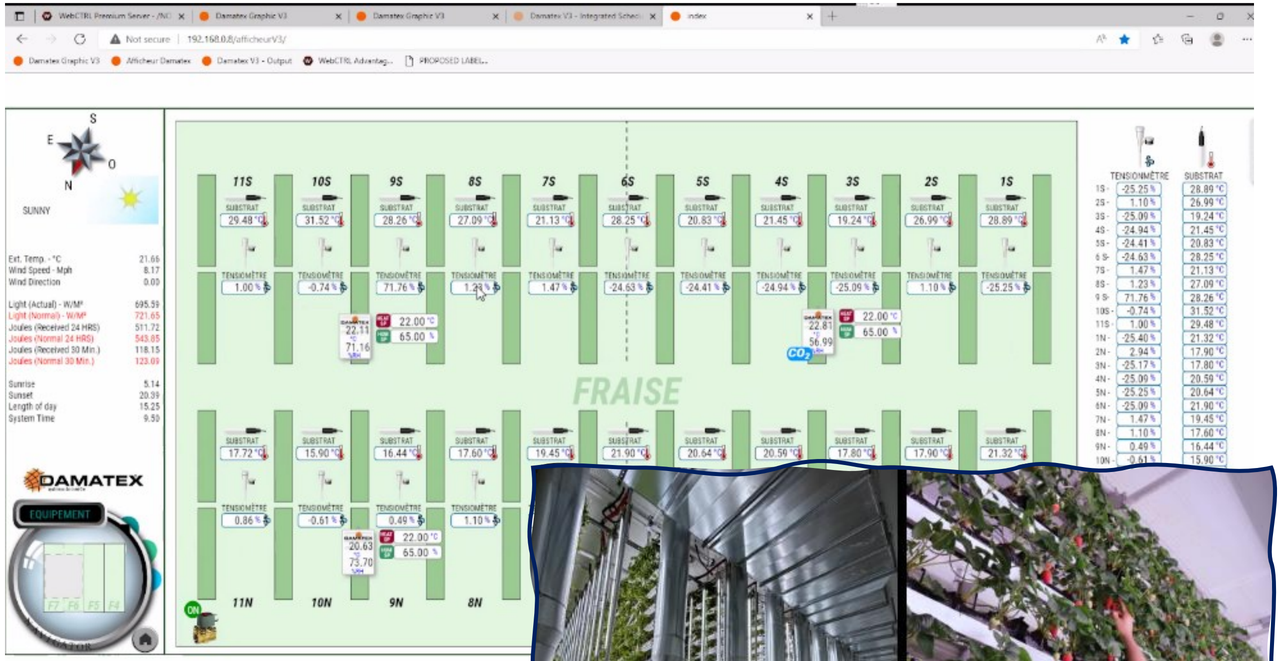


Goal modeling



Models




SUNNY
DAMATEX
EQUIPEMENT
FRAISE
SUBSTRAT
TENSIOMÈTRE
11S
10S
9S
8S
7S
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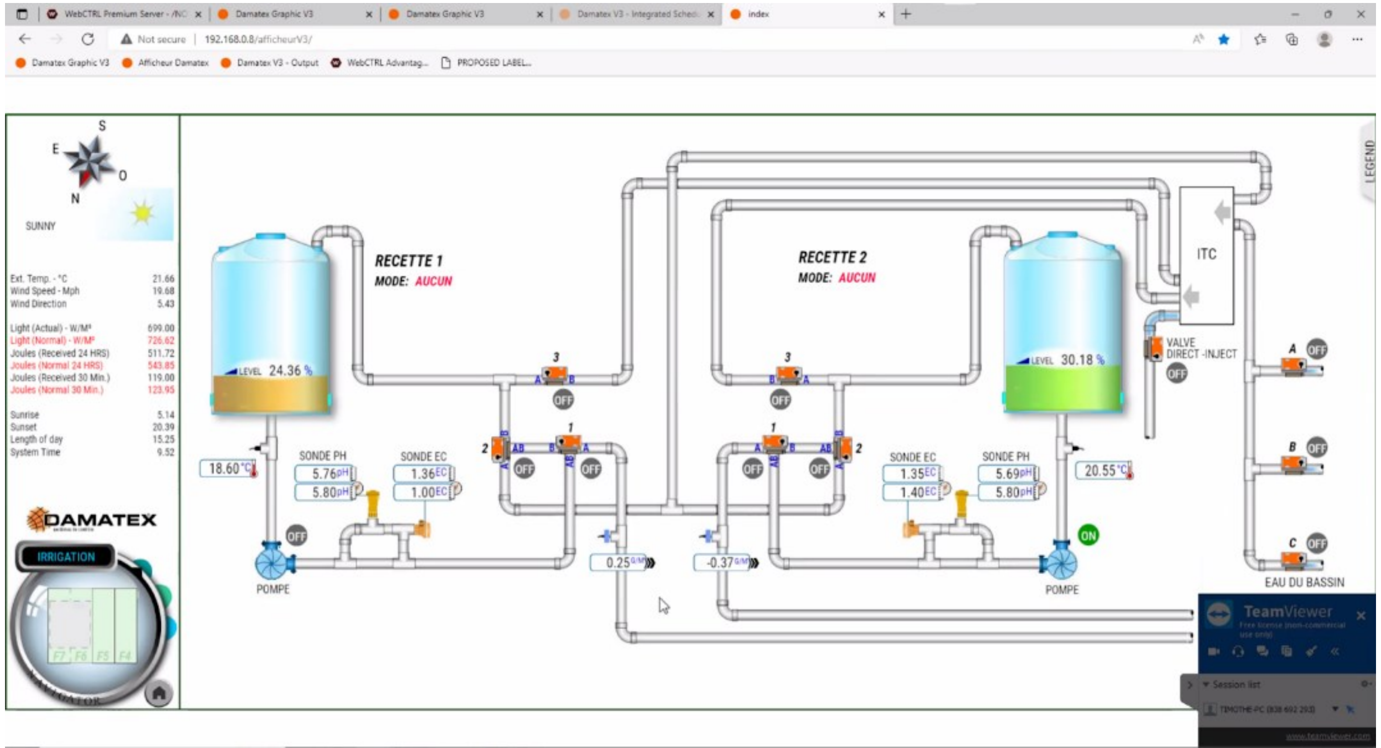
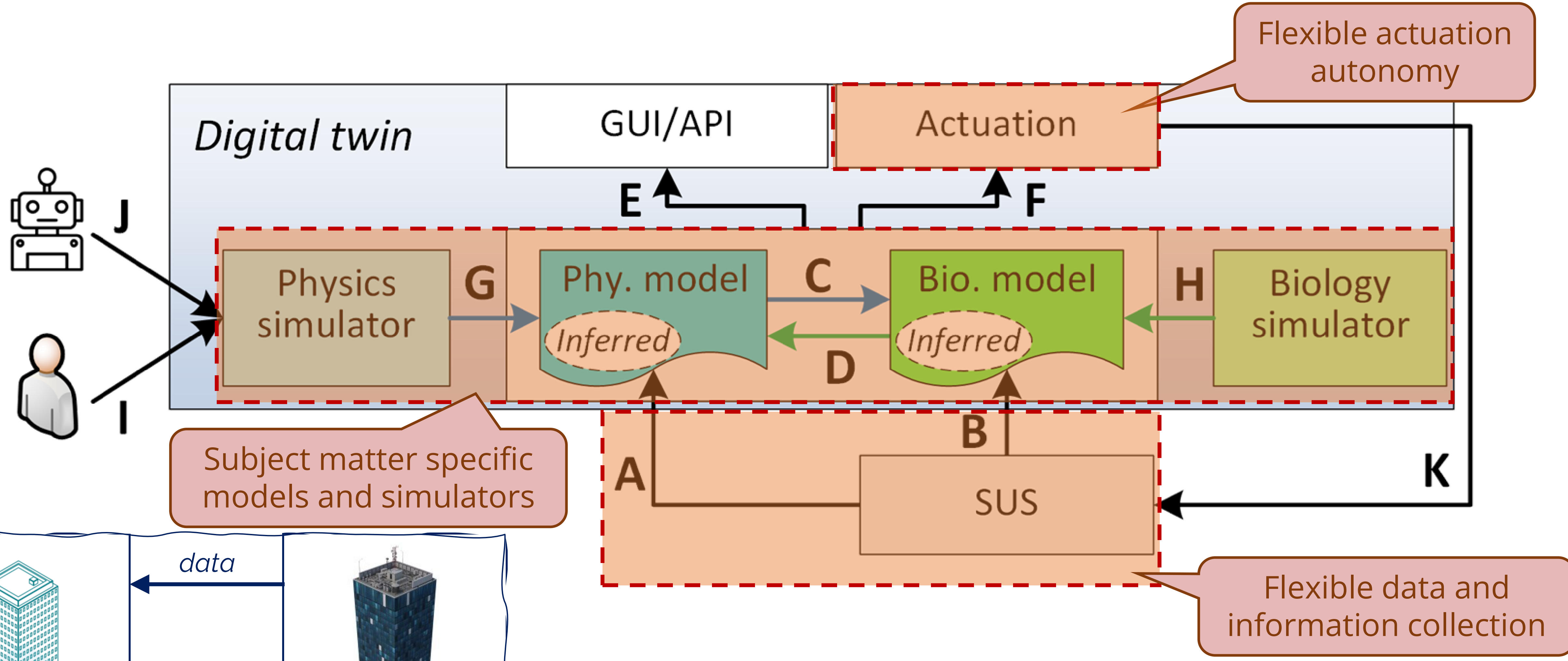
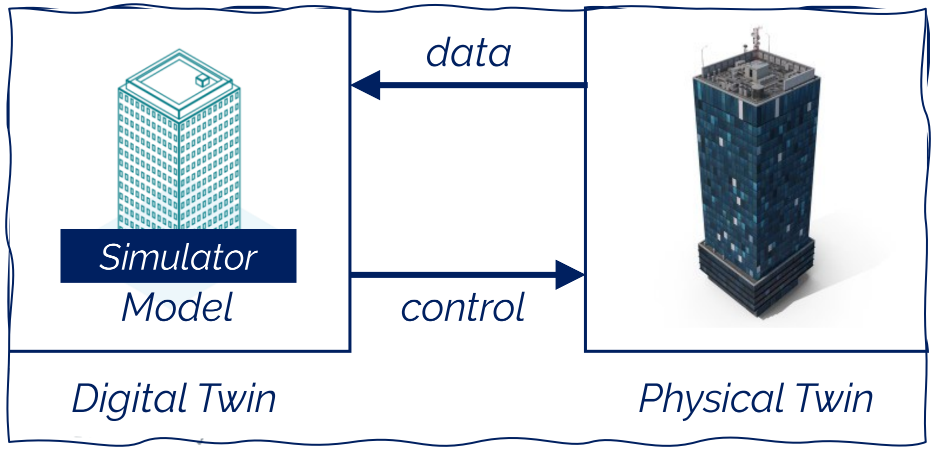
11N
10N
9N
8N


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

DT4CBPS: Conceptual framework and requirements





Environment

Room

HVAC

Lights

Irrigation

Crop

Energy

Growth

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

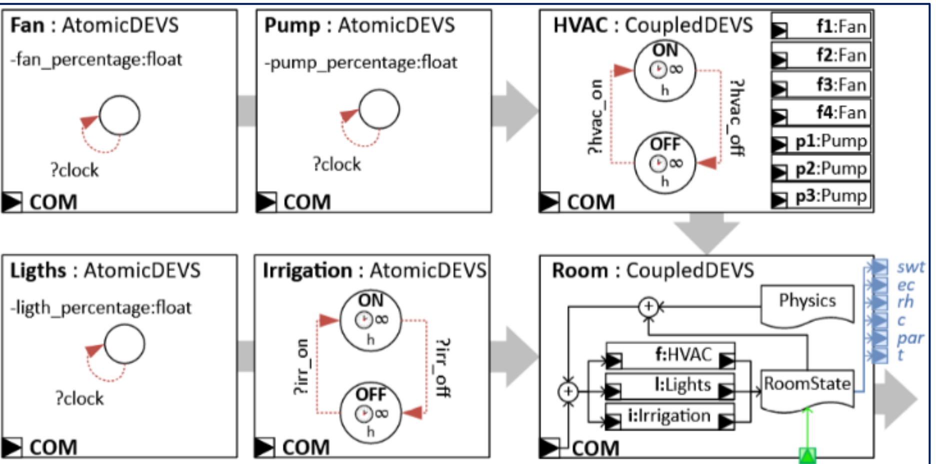
Functional Mock-Up Interface

Functional Mock-Up Interface

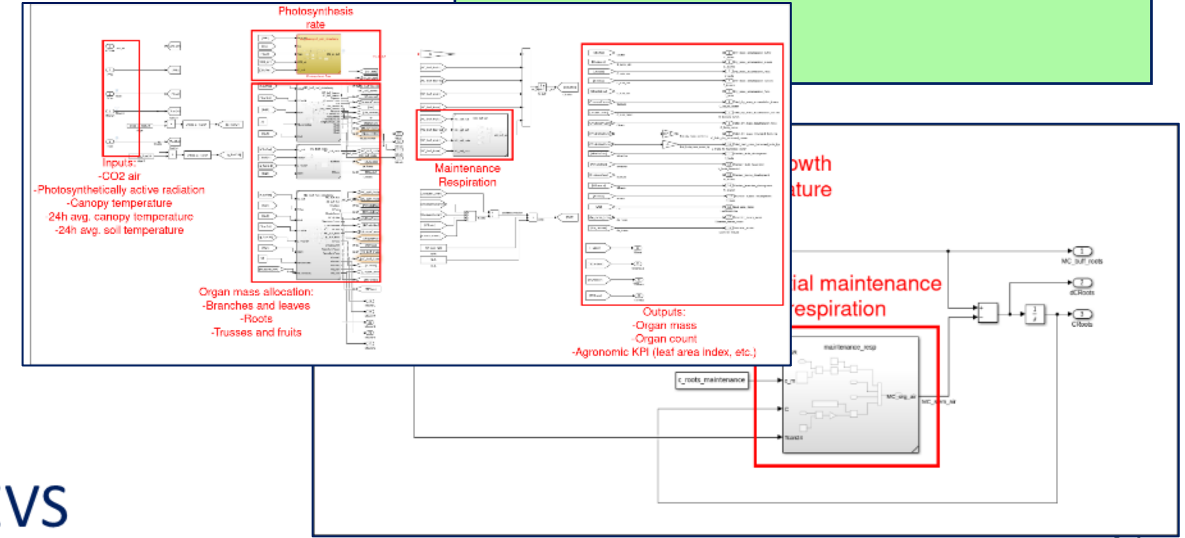
$$\frac{dy}{dt} = ky$$

MATLAB®

SIMULINK®



PythonPDEVS



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

https://doi.org/10.1109/MODELS58315.2023.00014


ACM/IEEE 26th International Conference on
Model-Driven Engineering Languages and Systems
BEST PRACTICE TRACK PAPER
Digital Twins for Cyber-Biophysical Systems:
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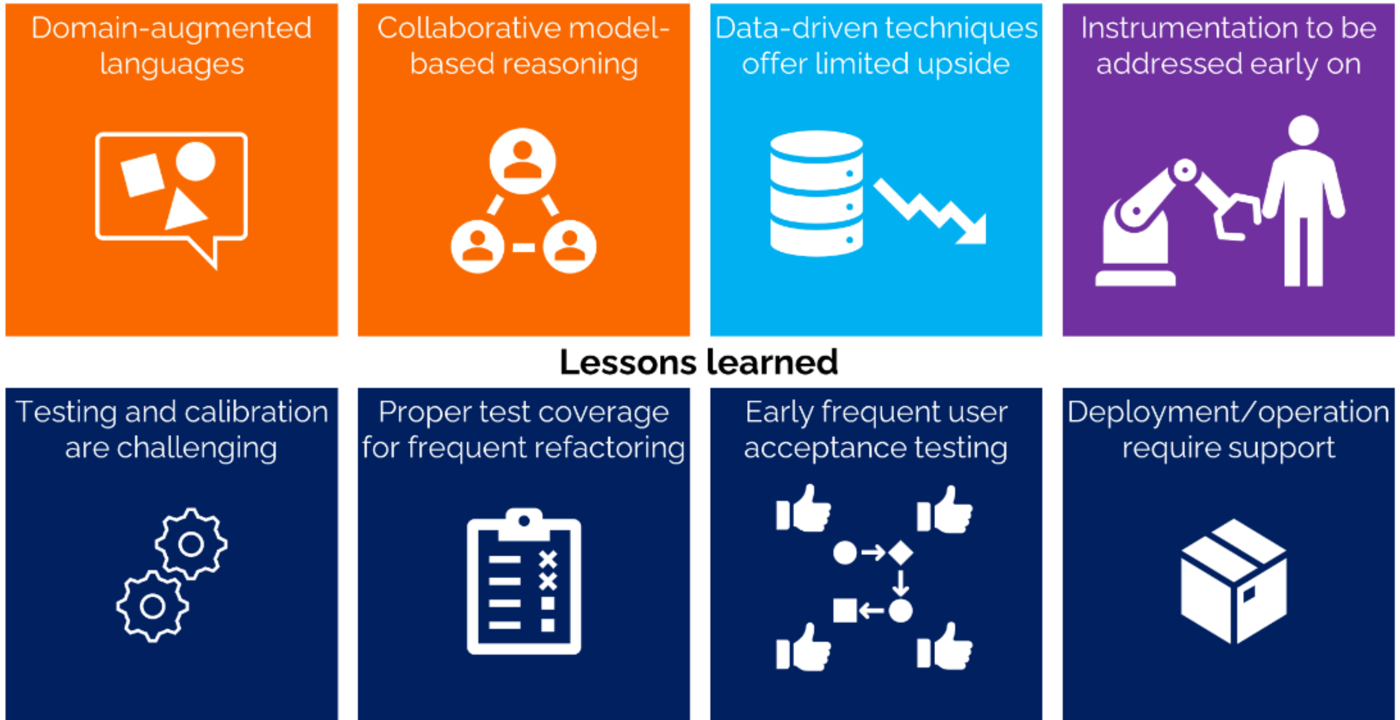
G. Taentzer PC Chair
T. Kühne PC Chair
A. Cicchetti General Chair
A. Pierantonio General Chair



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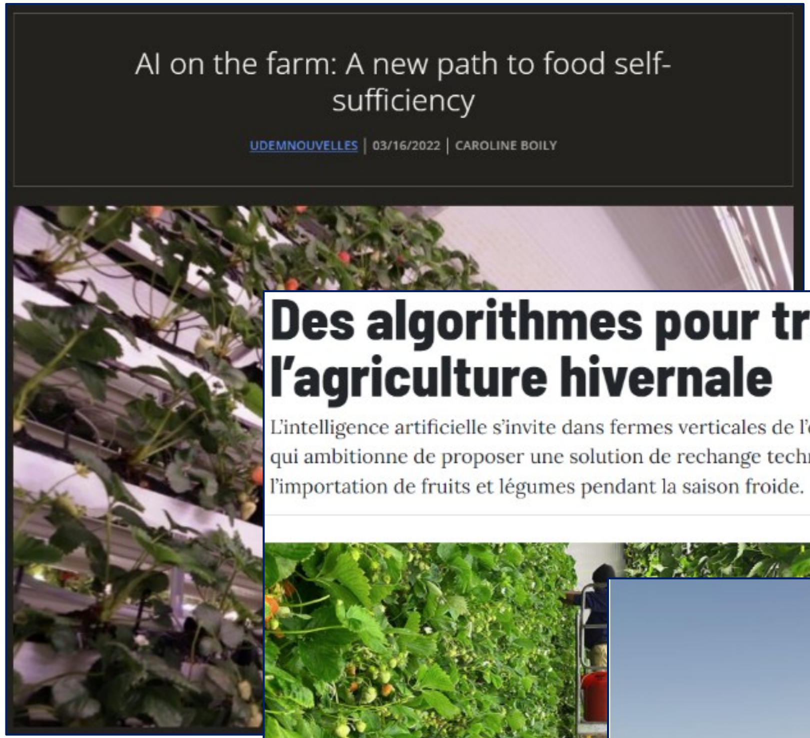


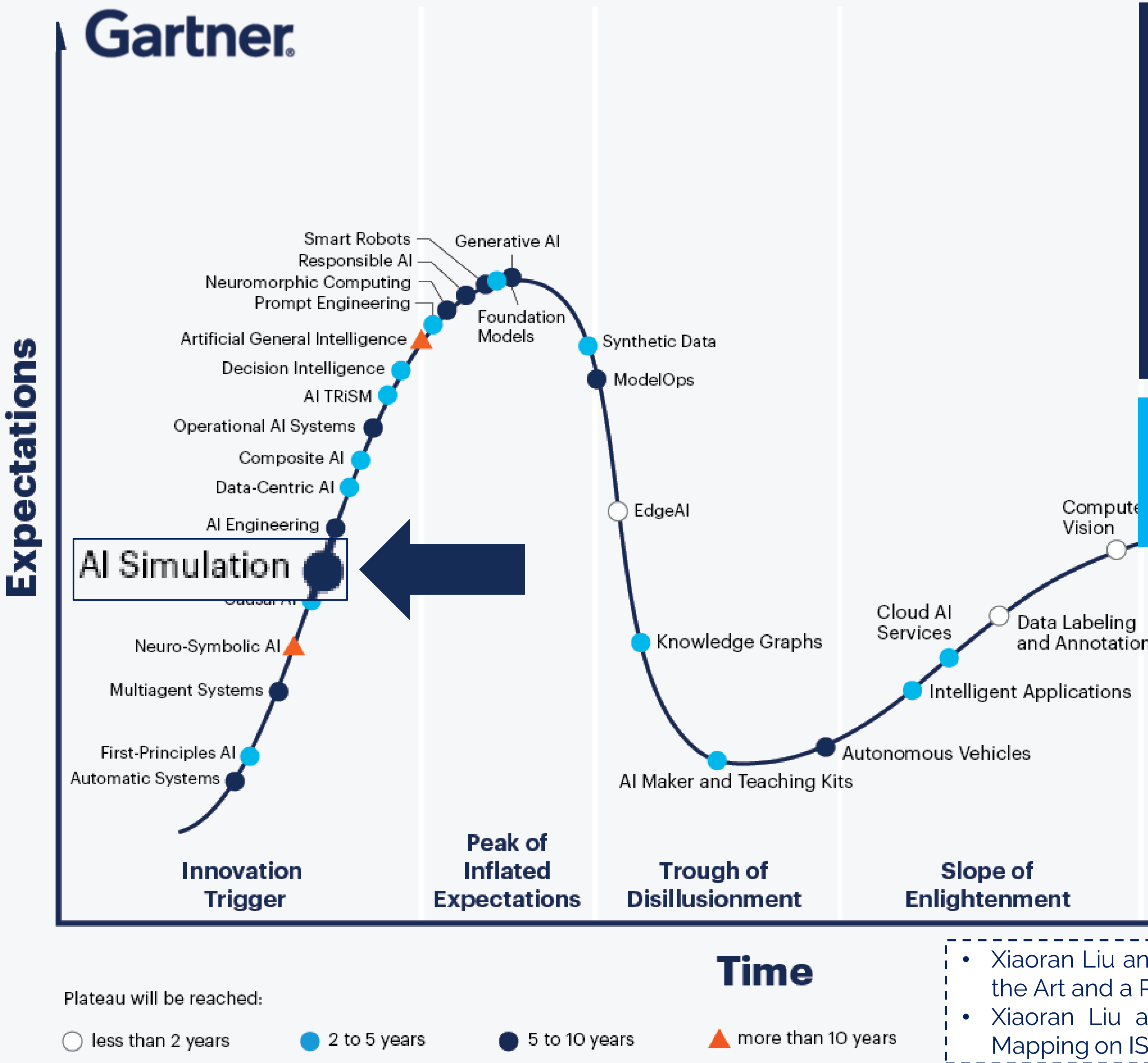
https://nouvelles.umontreal.ca/en/article/2022/03/16/ai-on-the-farm-a-new-path-to-food-self-sufficiency/

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

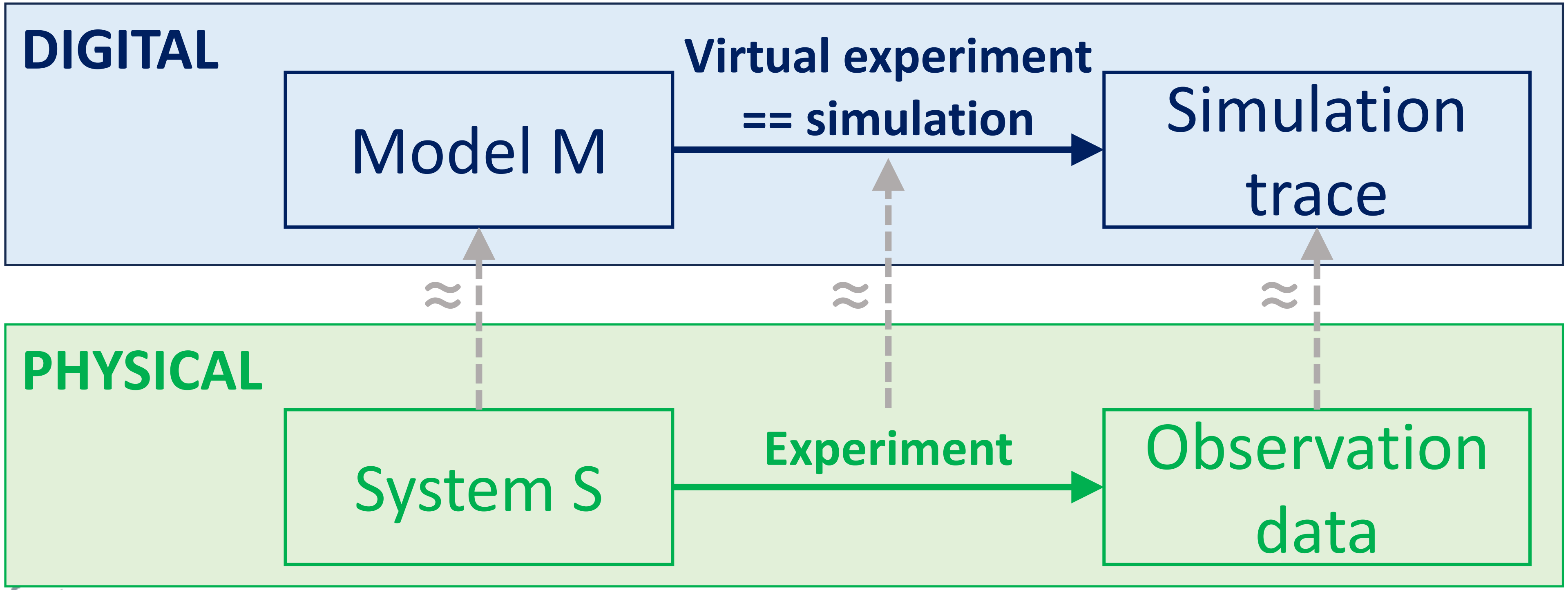
The combined application of AI and simulation technologies to jointly develop AI agents and the simulated environments in which they can be trained, tested and sometimes deployed.

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. 2025. [Under review]

Opportunity:
purposeful experimentation to acquire missing 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.

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.

EDTConf'24, September 23-24, 2024, Linz, Austria

ACM ISBN 978-x-xxxx-xxxx-x/YY/MM
https://doi.org/XXXXXXX.XXXXXXX

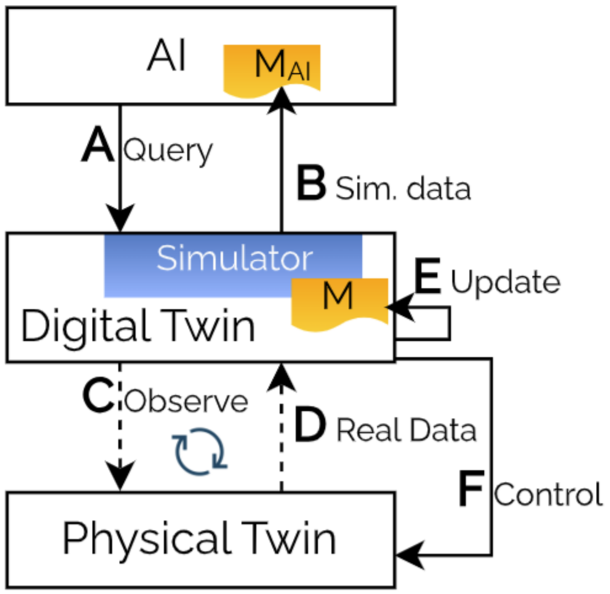
Domains/problems

Digital twins

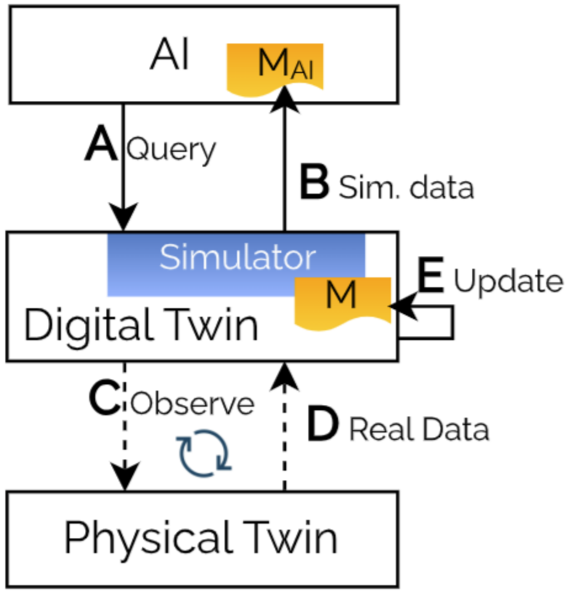
AI/ML

Lifecycle models

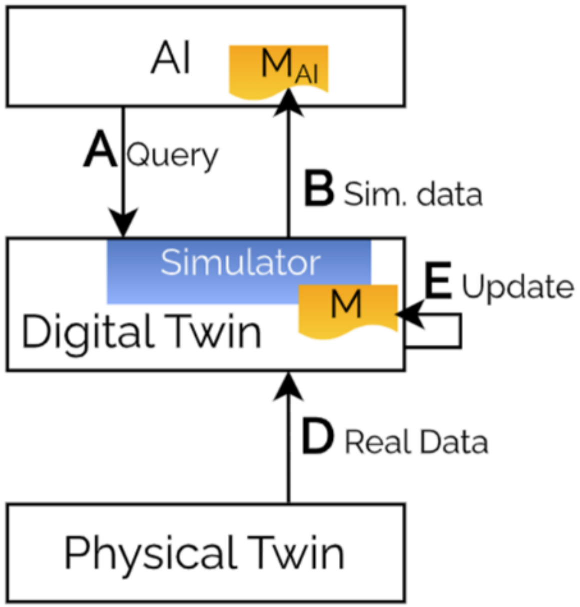
Challenges/limitations



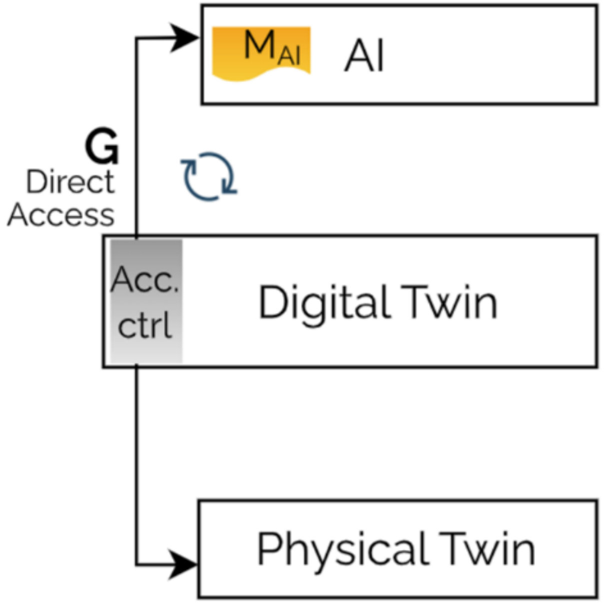
(a) Experimentable DT



(b) Experimentable DS



(c) Experimentable Model



(d) Policy DT

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

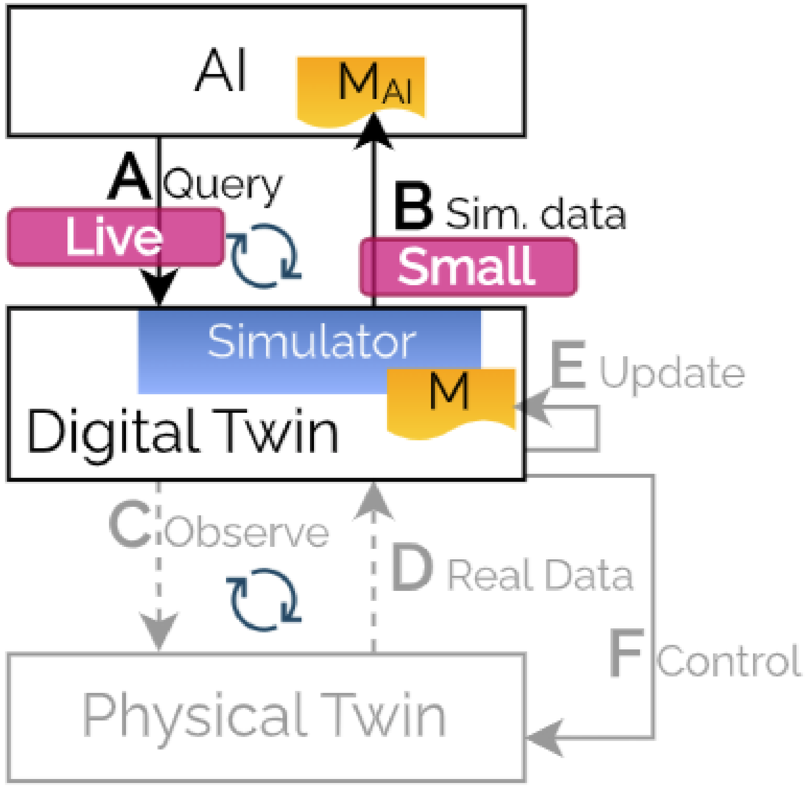
Digital twins

AI/ML

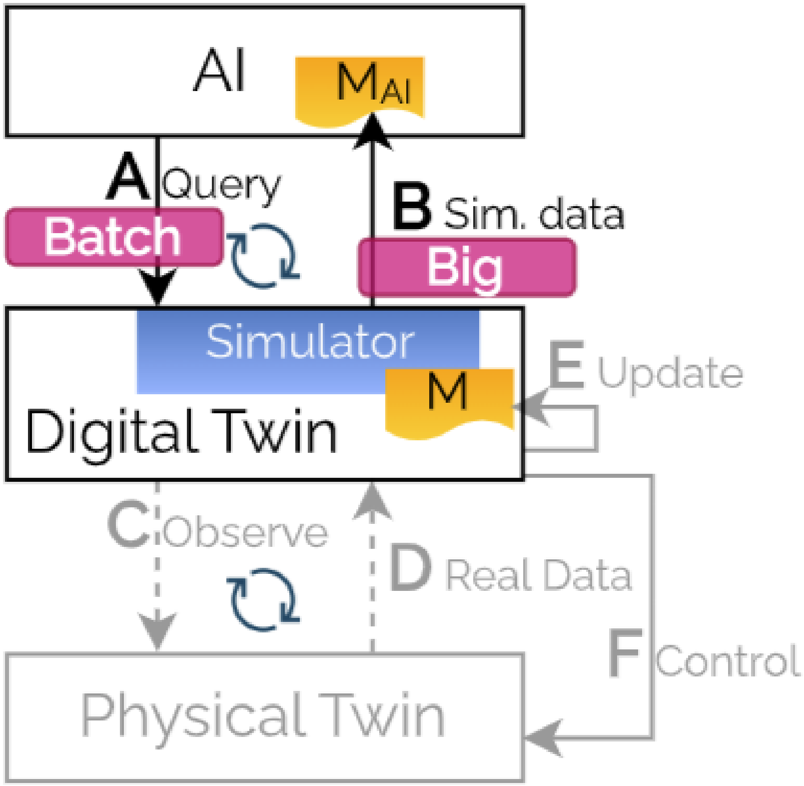
Lifecycle models

Challenges/limitations

Deep learning proliferates



(a) Reinforcement Learning



(b) Deep Learning

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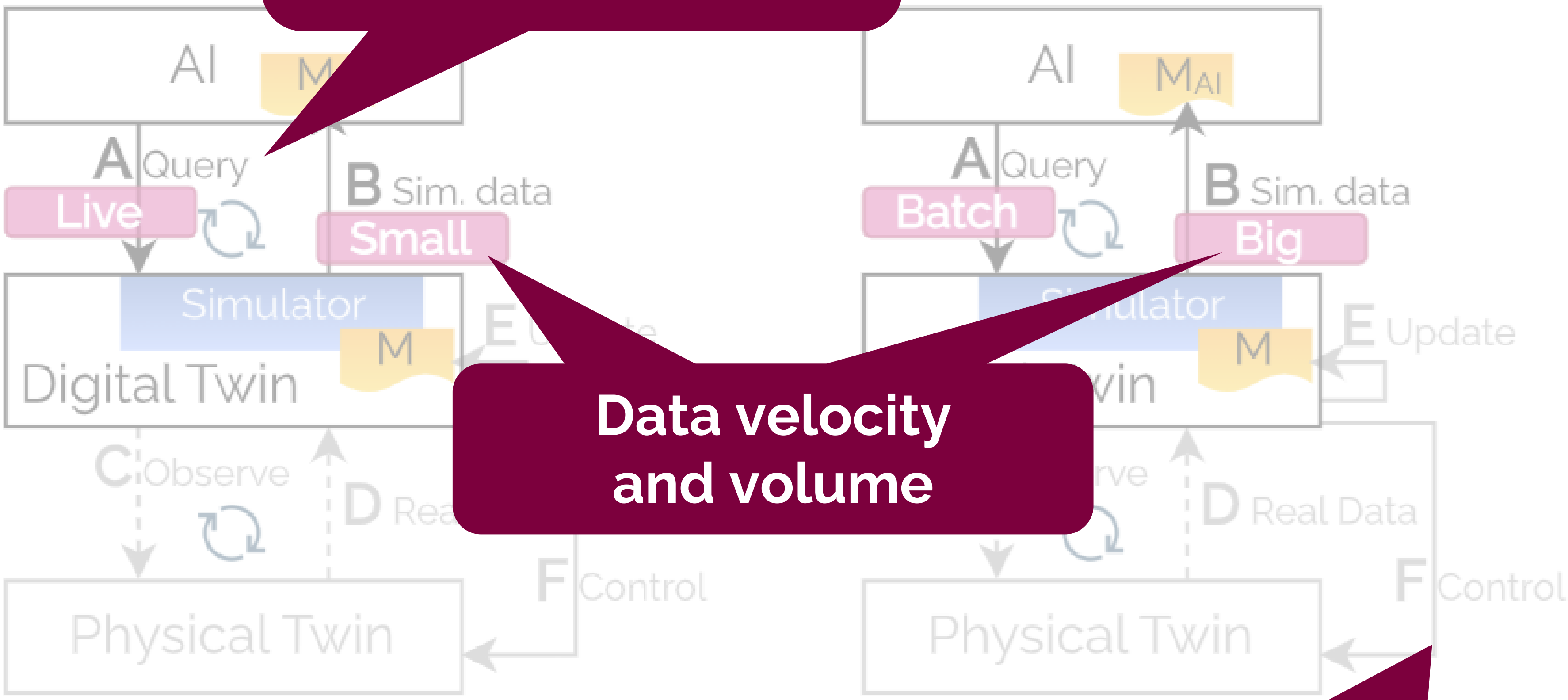
Domains/problems

Digital twins

AI/ML

Lifecycle models

Challenges/limitations



(a) Reinforcement Learning

Frequency of interactions: might be limited

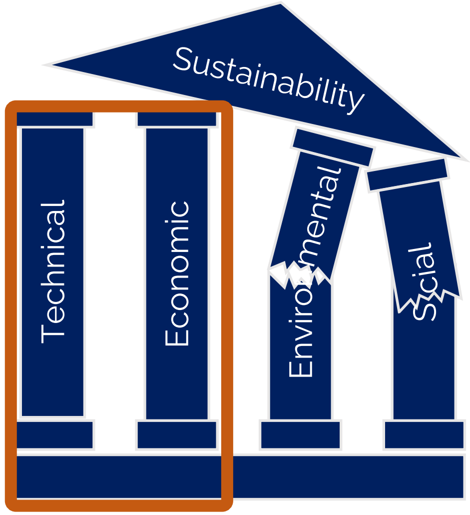
Data velocity and volume

Instrumentation

McMaster University

Sustainability
by and *of* Digital twins

Problem: our systems are not sustainable

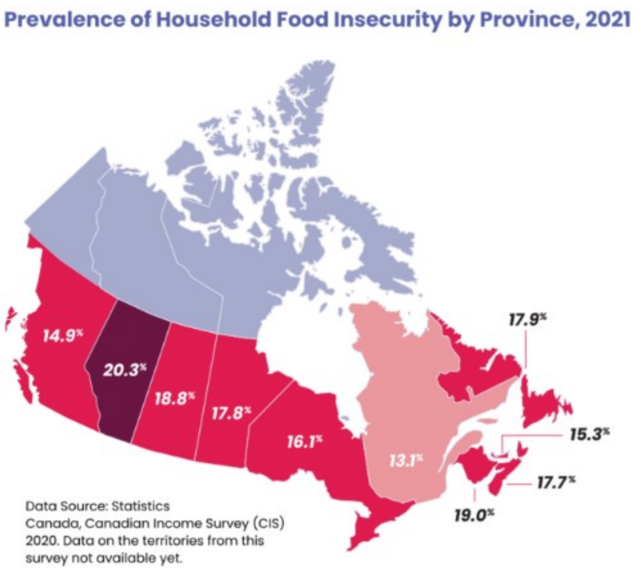


Systems Engineering

> *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.




NATURE AND ENVIRONMENT | EUROPE

Air pollution: Nearly everyone in Europe breathing bad air

Rodrigo Menegat Schuinski

09/07/2023

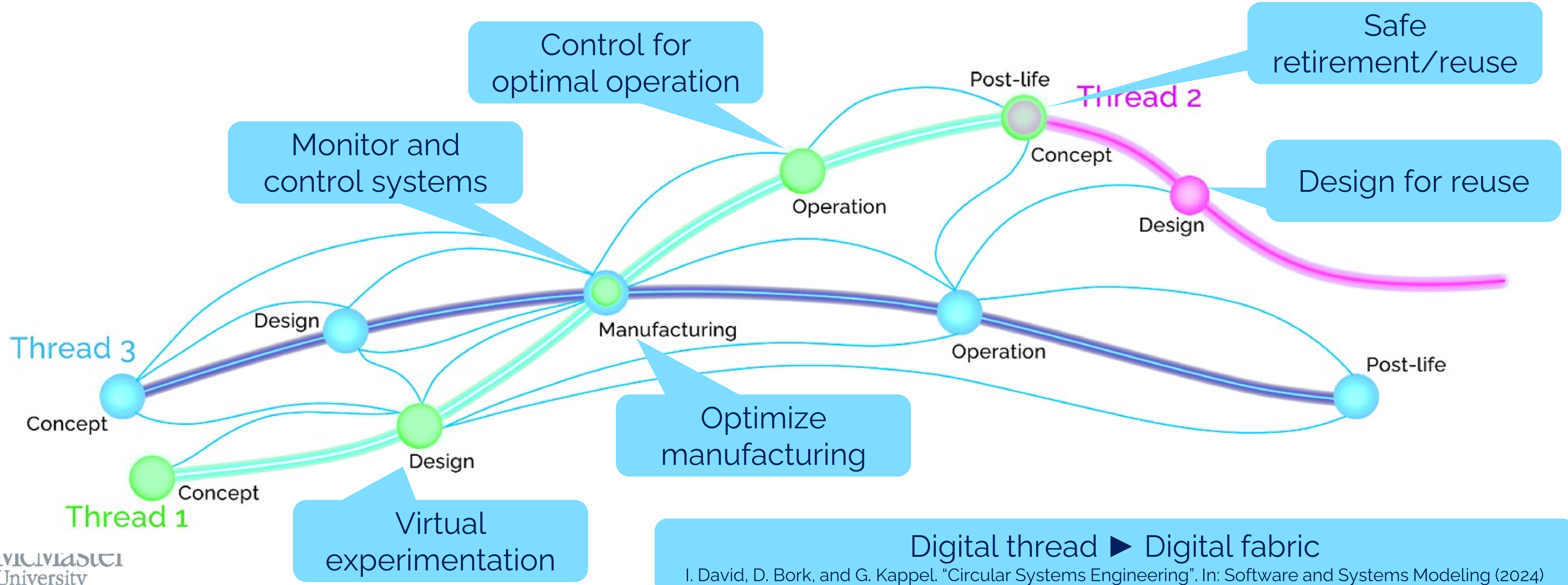
With the EU voting on new air quality rules, satellite data sho[w] **98%** [p]eople face pollution above limits recommended by the World Health Organization.

Digital technology to the rescue?

Digital Twins for Sustainable Systems

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

(CapGemini, 2022)

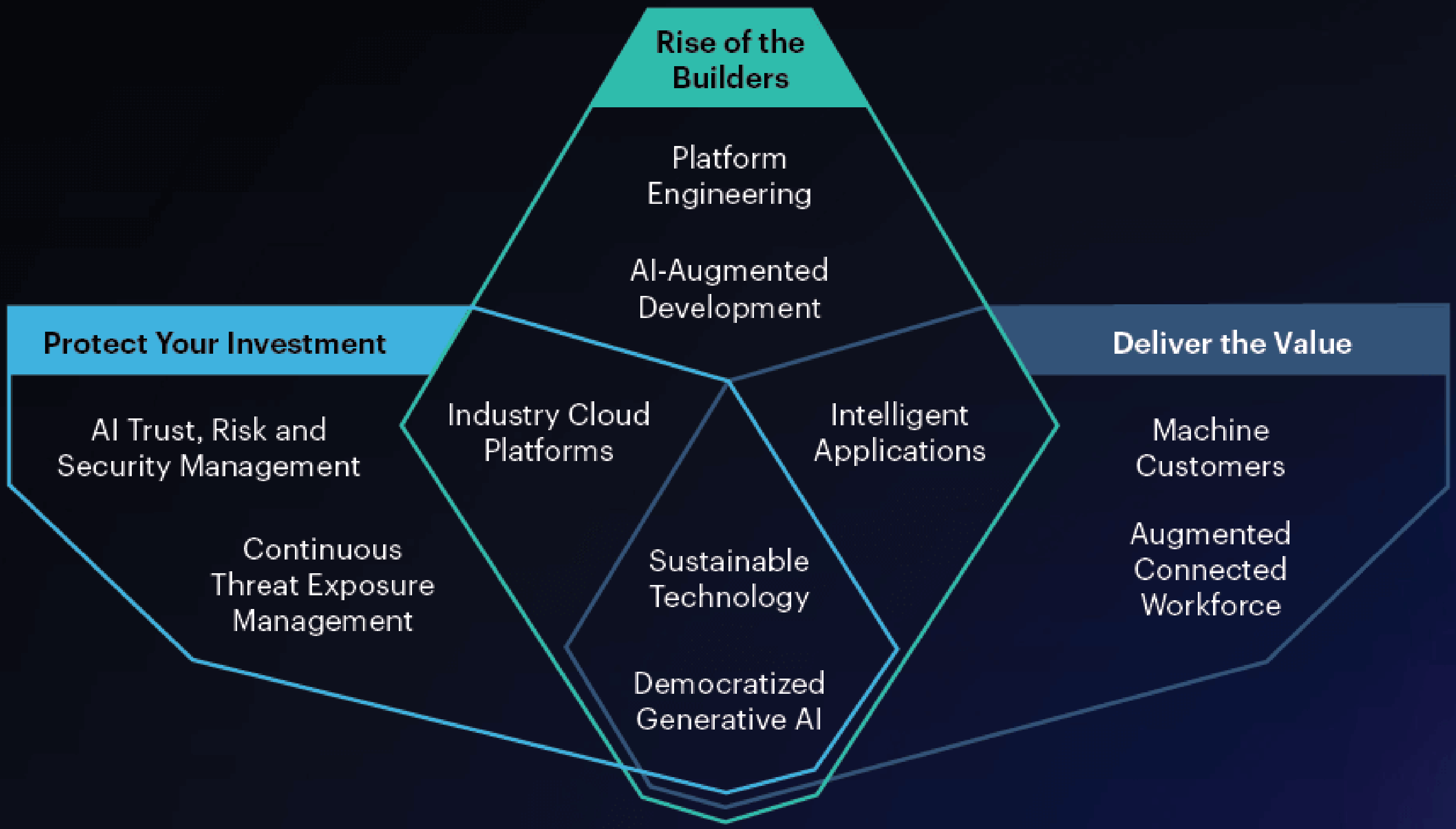


Digital thread ► Digital fabric

I. David, D. Bork, and G. Kappel. "Circular Systems Engineering". In: Software and Systems Modeling (2024)

McMaster University

Top Strategic Technology Trends 2024



Source: 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

Source: Gartner

Gartner

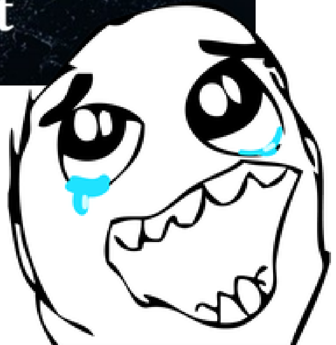
EMERGING TECHNOLOGIES

9 ways AI is helping tackle climate change

Feb 12, 2024

WORLD ECONOMIC FORUM

Digital technology to the rescue!



EMERGING TECHNOLOGIES

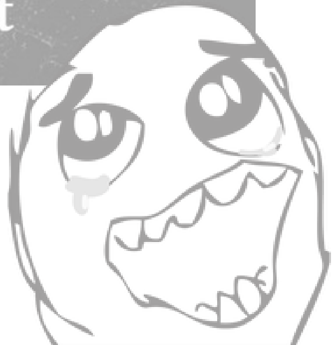
9 ways AI is helping tackle climate change

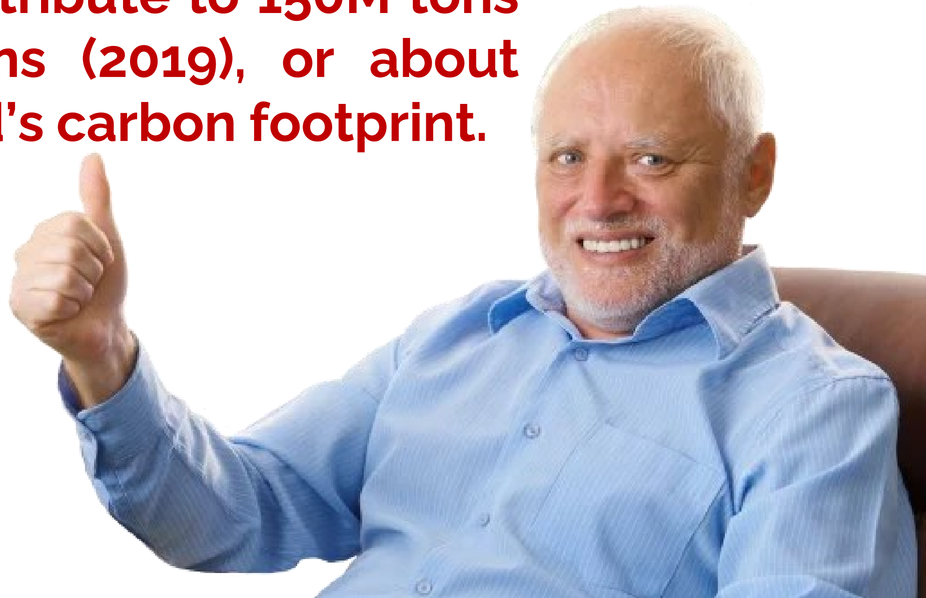
Feb 12, 2024

WORLD ECONOMIC FORUM

Digital technology to the rescue!

It is estimated that emails sent globally can contribute to 150M tons of CO_2 emissions (2019), or about 0.3% of the world's carbon footprint.





Unsustainable computing and ICT

Manufacturing

- 33% of global energy consumption
- 36% of global CO_2 emissions

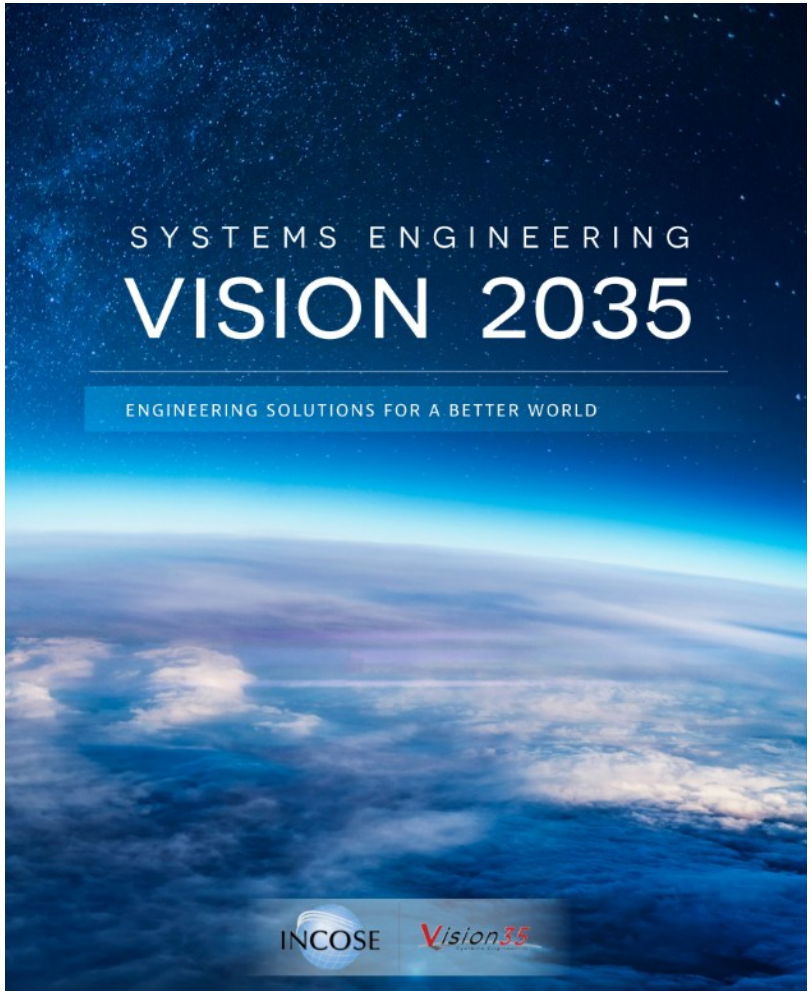
Hardware and e-devices

- *E-waste* is recognized by the World Economic Forum as the fastest-growing category of waste

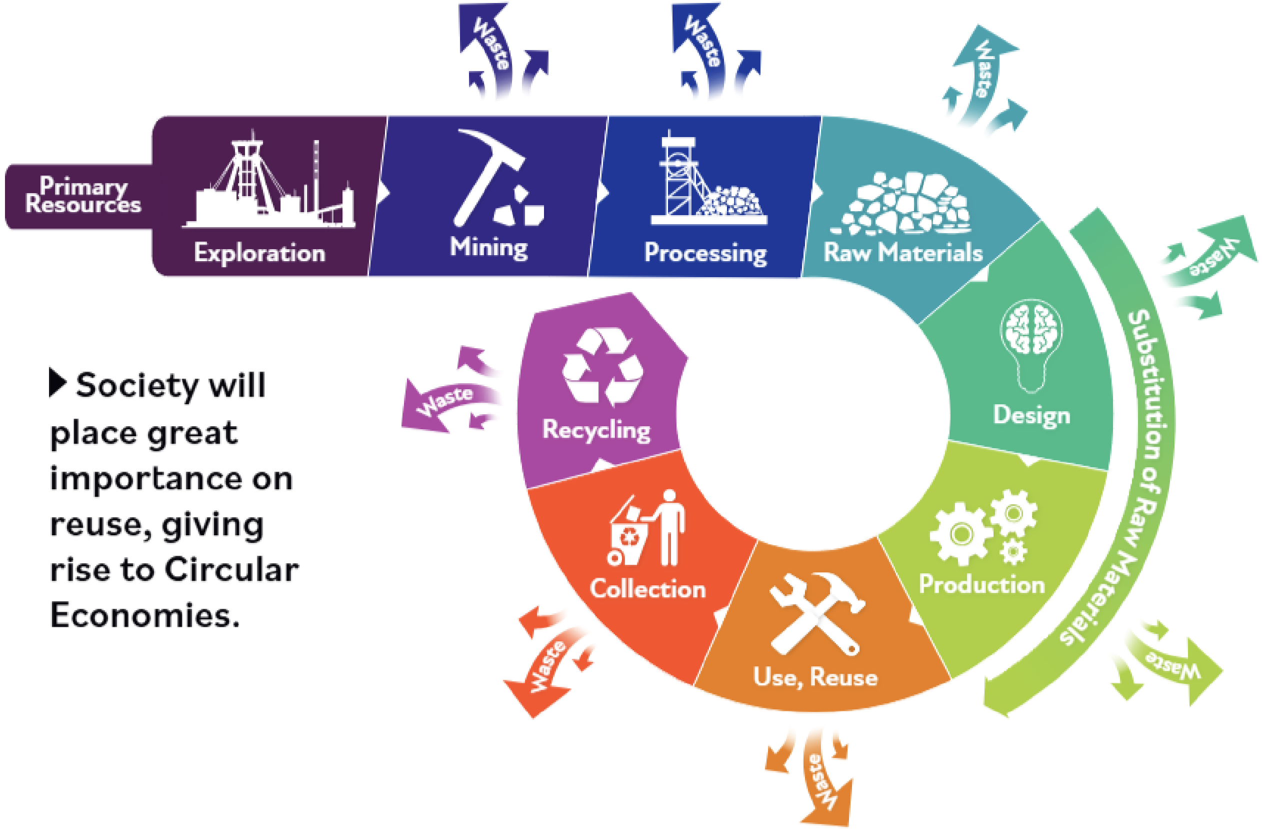
ICT

- 2-4% of global CO_2 emissions (~avionics sector)
- 2040 prediction: ~14%
- To follow suit, decrease CO_2 emissions by
  - -42% by 2030
  - -72% by 2040
  - -91% by 2050

We need to engineer sustainable systems.
By sustainable methods.


SYSTEMS ENGINEERING
VISION 2035
ENGINEERING SOLUTIONS FOR A BETTER WORLD
INCOSE
Vision35

ENVIRONMENTAL SUSTAINABILITY BECOMES A HIGH PRIORITY



- Society will place great importance on reuse, giving rise to Circular Economies.

- Impacts of human activity on climate will be ingrained in assessments of engineered systems and public/private policies.
- Many systems, both straightforward and novel, will arise to mitigate the deleterious impacts of climate change, such as global warming.

THE GLOBAL PUBLIC WILL TRUST AND REWARD SYSTEMS PROVIDERS AND OPERATORS THAT PRODUCE SUSTAINABLE SYSTEMS AND BEHAVE IN A SUSTAINABLE MANNER.

Demand for sustainable systems


GLOBAL MEGATREND 1

ENVIRONMENTAL SUSTAINABILITY BECOMES A HIGH PRIORITY

Consumption of non-renewable resources resulting from economic activity will increasingly require better global management, recycling strategies, sustainable policies, local actions, and supporting systems, such as energy conversion and infrastructure for clean transportation and manufacturing.

Environmental change will result in shifts in living conditions, and impacts bio-diversity, climate, global heat transport, the availability of fresh water, and other natural resources necessary for human sustenance and well-being.

Overall environmental quality will be a priority, requiring global cooperation. The trend toward greater concern for environmental sustainability will result in several key societal and system imperatives.

Engineering for sustainability, a system characteristic, will create a new generation of engineers who routinely assess the societal impacts of engineered systems.

- Impacts of human activity on climate will be ingrained in assessments of engineered systems and public/private policies.
- Many systems, both straightforward and novel, will arise to mitigate the deleterious impacts of climate change, such as global warming.
- Priority will be placed on systems that are more efficient at resource utilization and responsible waste disposal. Though enterprises will continue to struggle with business and consumer pressures to increase consumption, versus environmental prerogatives to reduce waste.
- Society will place great importance on reuse, giving rise to Circular Economies.
- The global fossil-fuel based energy economy will be transformed to one based on clean and renewable sources.

INCOSE Systems Engineering Vision 2035

Bus Inf Syst Eng 65(1):1–6 (2023)
https://doi.org/10.1007/s12599-022-00784-6

EDITORIAL

Sustainable Systems Engineering

Opportunities and Challenges

Wil M. P. van der Aalst · Oliver Hinz · Christof Weinhardt

Modelling Sustainability in Cyber-Physical Systems: A Systematic Mapping Study

Ankica Barišić[a], Jácome Cunha[g,h], Ivan Ruchkin[b], Ana Moreira[f,e], João Araújo[f,e], Moharram Challenger[c], Dušan Savić[d], Vasco Amaral[f,e]

White Paper DRAFT for Discussion

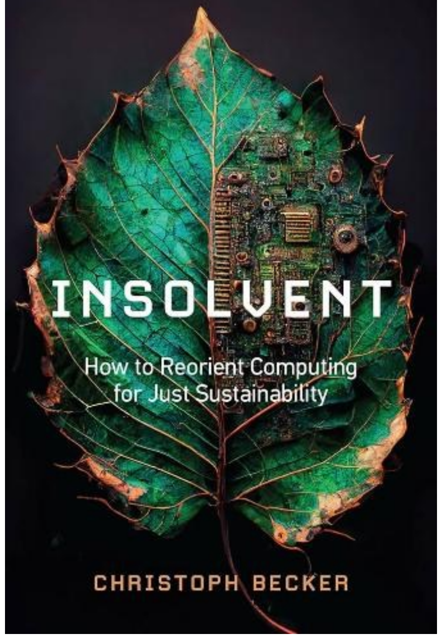
by concerned Education and Enterprise Communities

This Paper is a Compendium to the Systems Engineering Vision 2035

Building the Systems Engineering Workforce of the Future

Education, Training and Development of System Engineers

Compiled and edited by Prof. Dipl.-Ing. Heinz Stoewer, M.Sc. SAC GmbH and TU Delft, and co-edited by David Nichols, JPL/Caltech



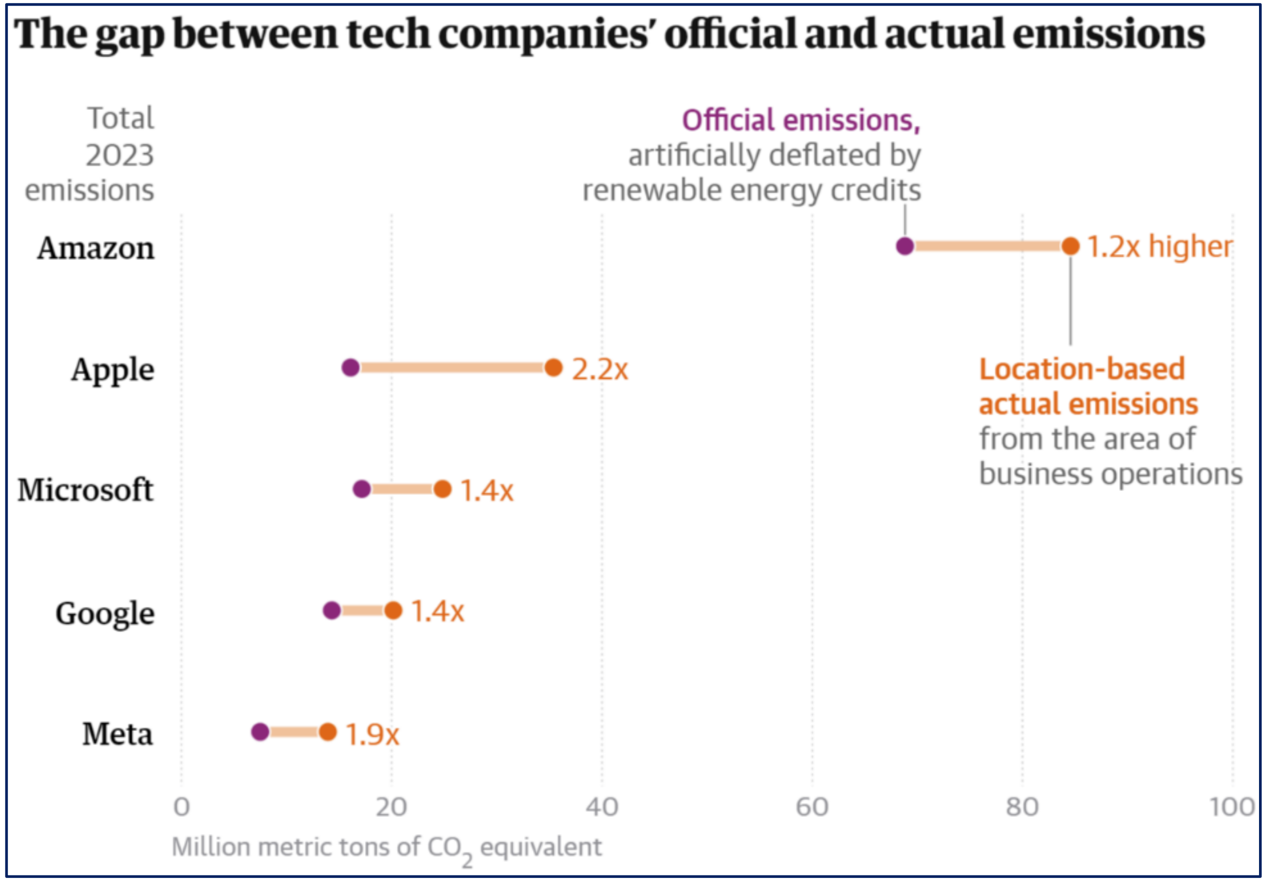
> *"computing's dominant frame of thinking is **conceptually insufficient** to address our current challenges (…) and computing continues to incur societal debts it cannot pay back*

> *"I believe, similarly to the EDI statements we have to write today for project proposals and applications, soon we will have to write sustainability statements. And this is not fifteen years from now, but closer to five.*

McMaster University

We need a better understanding of "sustainability"

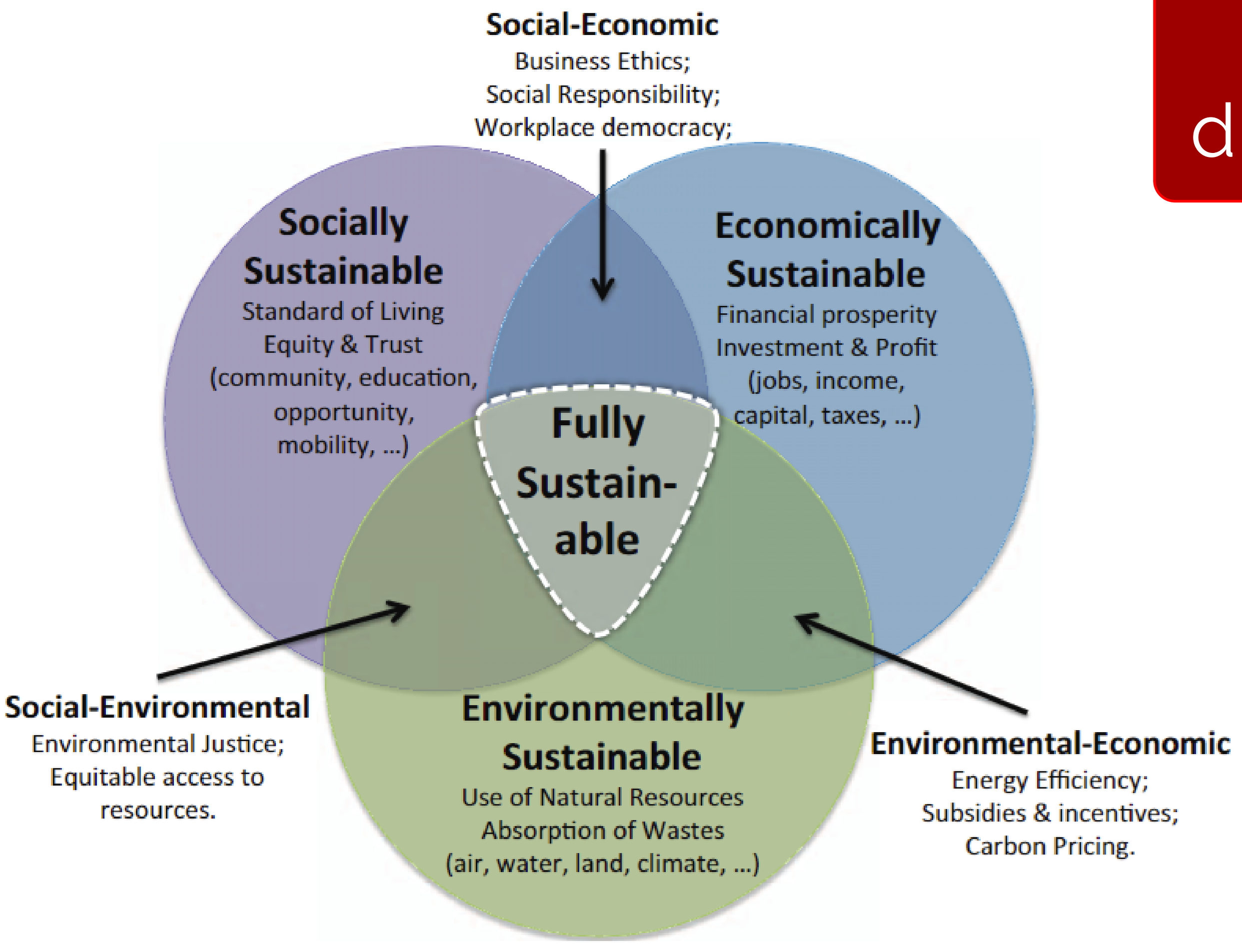
Data center emissions probably 662% higher than big tech claims. Can it keep up the ruse?



Emissions from in-house data centers of Google, Microsoft, Meta and Apple may be 7.62 times higher than official tally

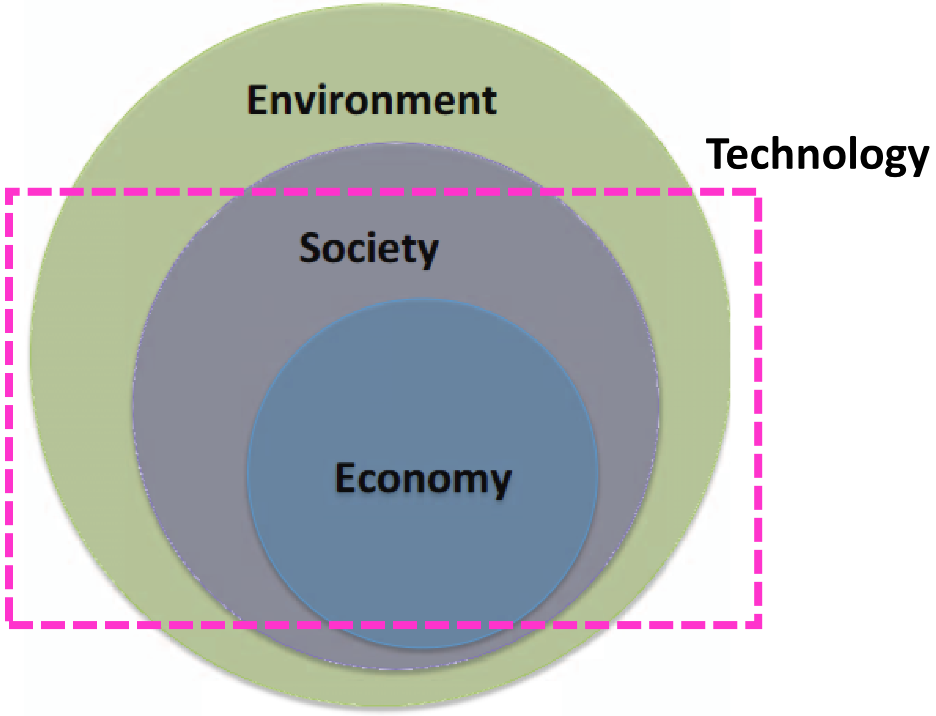
https://www.theguardian.com/technology/2024/sep/15/data-center-gas-emissions-tech

We need to **model** "sustainability"



Weak notion of sustainability

Complexity → diverse expertise is needed



Strong notion of sustainability

McMaster University

Participatory and Collaborative Modeling of Sustainable Systems: A Systematic Review

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ABSTRACT

Sustainability has become a key characteristic of modern systems. Unfortunately, the convoluted nature of sustainability limits its understanding and hinders the design of sustainable systems. Thus, cooperation among a diverse set of stakeholders is paramount to sound sustainability-related decisions. Collaborative modeling has demonstrated benefits in facilitating cooperation between technical experts in engineering problems; but fails to include non-technical stakeholders in the modeling endeavor. In contrast, participatory modeling excels in facilitating high-level modeling among a diverse set of stakeholders, often of non-technical profiles; but fails to generate actionable engineering models. To instigate a convergence between the two disciplines, we systematically survey the field of collaborative and participatory modeling for sustainable systems. By analyzing 24 primary studies (published until June 2024), we identify common challenges, cooperation models, modeling formalisms and tools; and recommend future avenues of research.

CCS CONCEPTS

• **General and reference → Surveys and overviews**; • **Social and professional topics → Sustainability**.

KEYWORDS

collaboration, MDE, model-driven, model-based, participatory modeling, survey, sustainability, systematic literture review

ACM Reference Format:
Rajitha Manellanga and Istvan David. 2024. Participatory and Collaborative Modeling of Sustainable Systems: A Systematic Review. In *ACM/IEEE 27th International Conference on Model Driven Engineering Languages and Systems (MODELS Companion '24), September 22–27, 2024, Linz, Austria.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3652620.3688557

1 INTRODUCTION

Sustainability is the capacity to endure [57] and preserve a system's functionality over time [52]. Sustainability has become one of the key characteristics and a major concern in modern systems [39]. An apt demonstration of this trend is the position the European Commission takes in identifying sustainability as one of the two central topics for a resilient European industry within the framework of Industry 5.0 [44]. Expert voices are also calling to action in developing more sustainable systems and engineering methods [56, 78].

Unfortunately, design for sustainability is significantly challenged by the stratified and multi-systemic nature of sustainability [39], i.e., having different meanings at different levels of abstraction and having different meanings for stakeholders of different domains. Various forms of *cooperative modeling* offer a treatment for these challenges. Modeling allows for treating the problem of stratified meanings by the mechanisms of multi-abstraction and multi-semantics [80]. As such, the role of modeling in the analysis and design of sustainable systems is clearly recognized [28]. Cooperation allows for treating multiple meanings by involving a diverse set of stakeholders at strategic points of the design process.

In the absence of sufficiently diverse cooperation, complex endeavors inevitably fail. For example, Nutt [64] reports that about half of policy decisions fail to achieve the desired results as ignored stakeholder knowledge and interests lead to erroneous decision-making. In response to the need for a diverse involvement of stakeholders, *participatory modeling* [51] facilitates a high-level modeling approach, e.g., through systems dynamics [63], in which non-experts and non-technical stakeholders can be part of the decision-making and design process. While the high level of abstraction and informal modeling benefit diversity, they limit the technical depth modeling can achieve, preventing such cooperative endeavors from shifting into an effective *design* phase. The need for combining participatory modeling with a more technical cooperative modeling paradigm for the design of sustainable systems has been clearly articulated before, e.g., by Midgley [60] and Nabavi et al. [63].

Collaborative modeling [36, 46] is a prime candidate to become the cooperative modeling approach required in the design of sustainable systems. Collaborative modeling is a method or technique in which multiple stakeholders manage, collaborate, and are aware of each others' work on a set of shared formal models [46]. While the benefits of collaborative modeling in technical problems have been demonstrated in academia and industry alike, state-of-the-art collaborative modeling techniques are severely limited in their human facets and communication aspects [37], forming a serious barrier for non-technical stakeholders to participate in collaborative modeling endeavors. This, in turn, restricts collaborative modeling to technical problems and limits the potential of collaborative modeling to be applied in sustainability decisions.

There is a synergy between participatory and collaborative modeling that can benefit the design of sustainable systems. Collaborative modeling can support the detailed design of sustainable systems, but it needs to become stakeholder-focused and inclusive

ACM ISBN 979-8-4007-0622-6/24/09
https://doi.org/10.1145/3652620.3688557

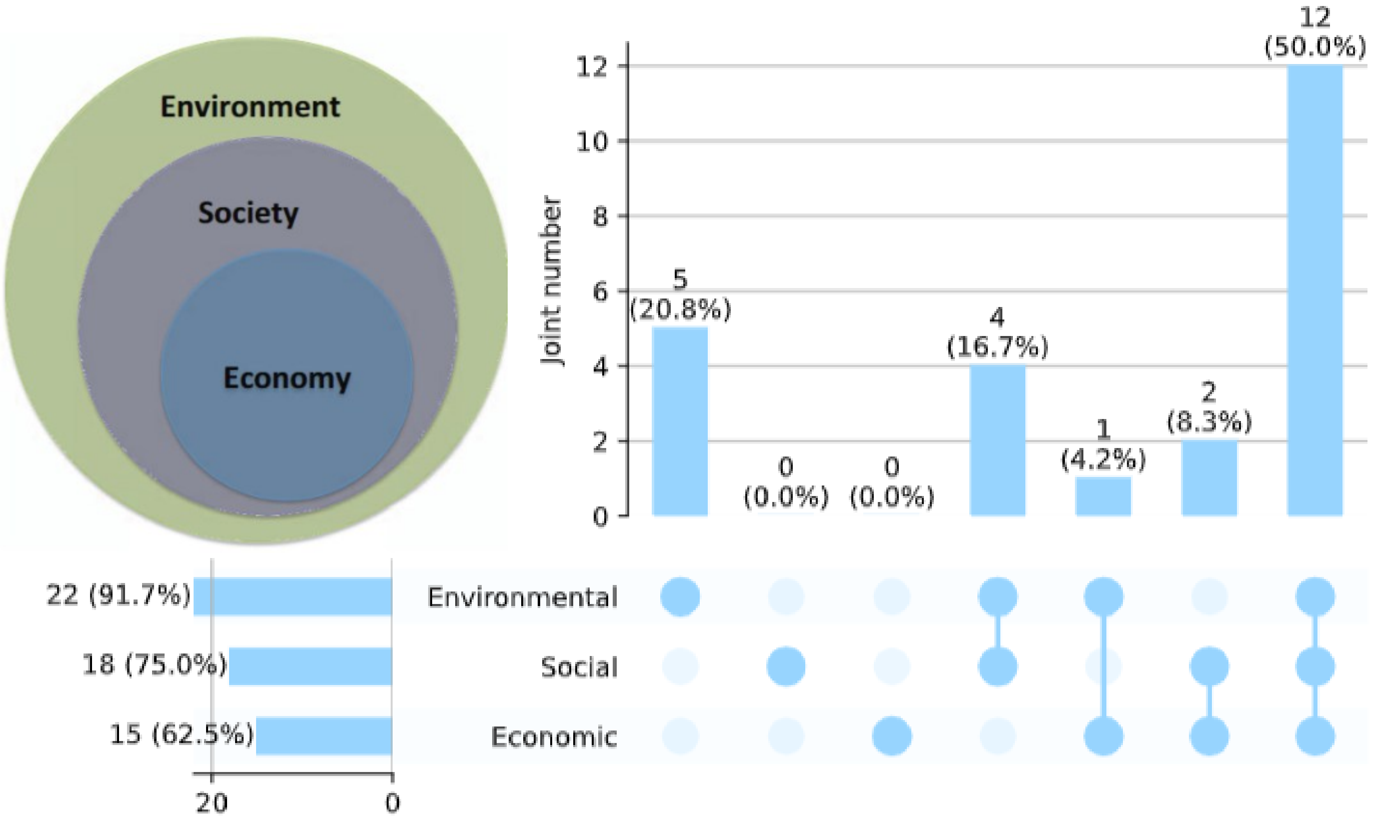
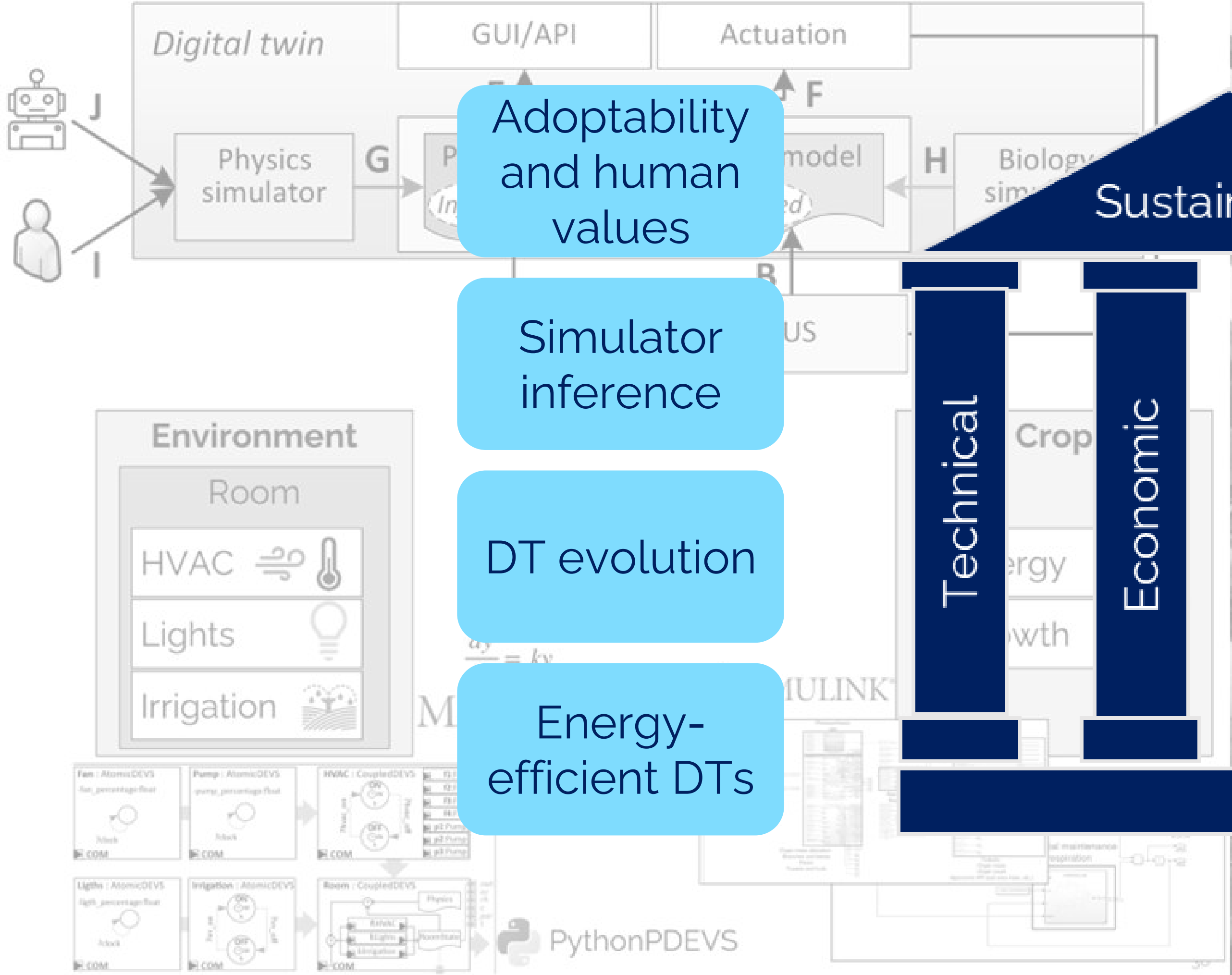


Figure 2: Breakdown of joint sustainability dimensions

R. Manellanga and I. David. "**Participatory and Collaborative Modeling of Sustainable Systems: A Systematic Review**". In: ACM/IEEE International Conference on Model Driven Engineering Languages and Systems Companion, MODELS-C. ACM, 2024, pp. 645–654. 10.1145/3652620.3688557

So, what about the sustainability *of* digital twins?

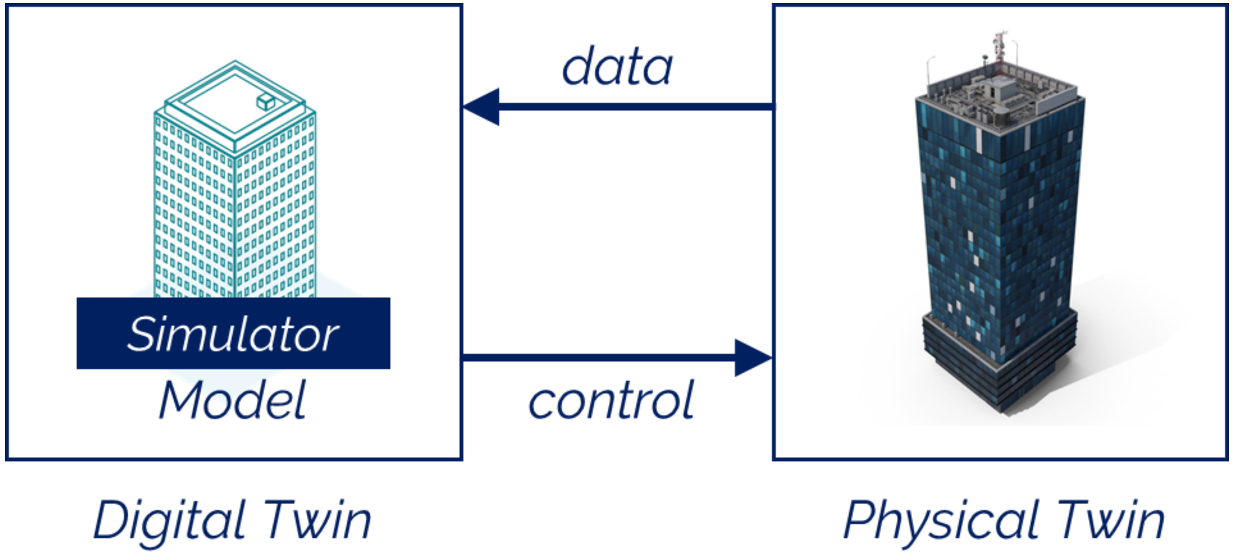
McMaster University

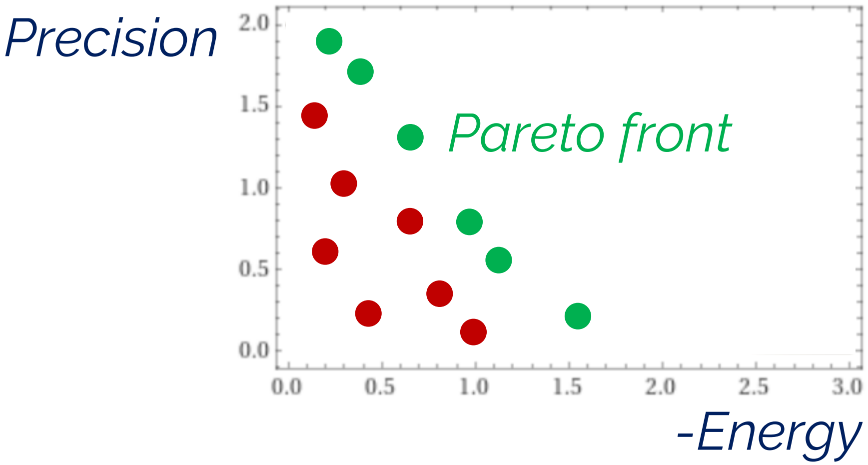


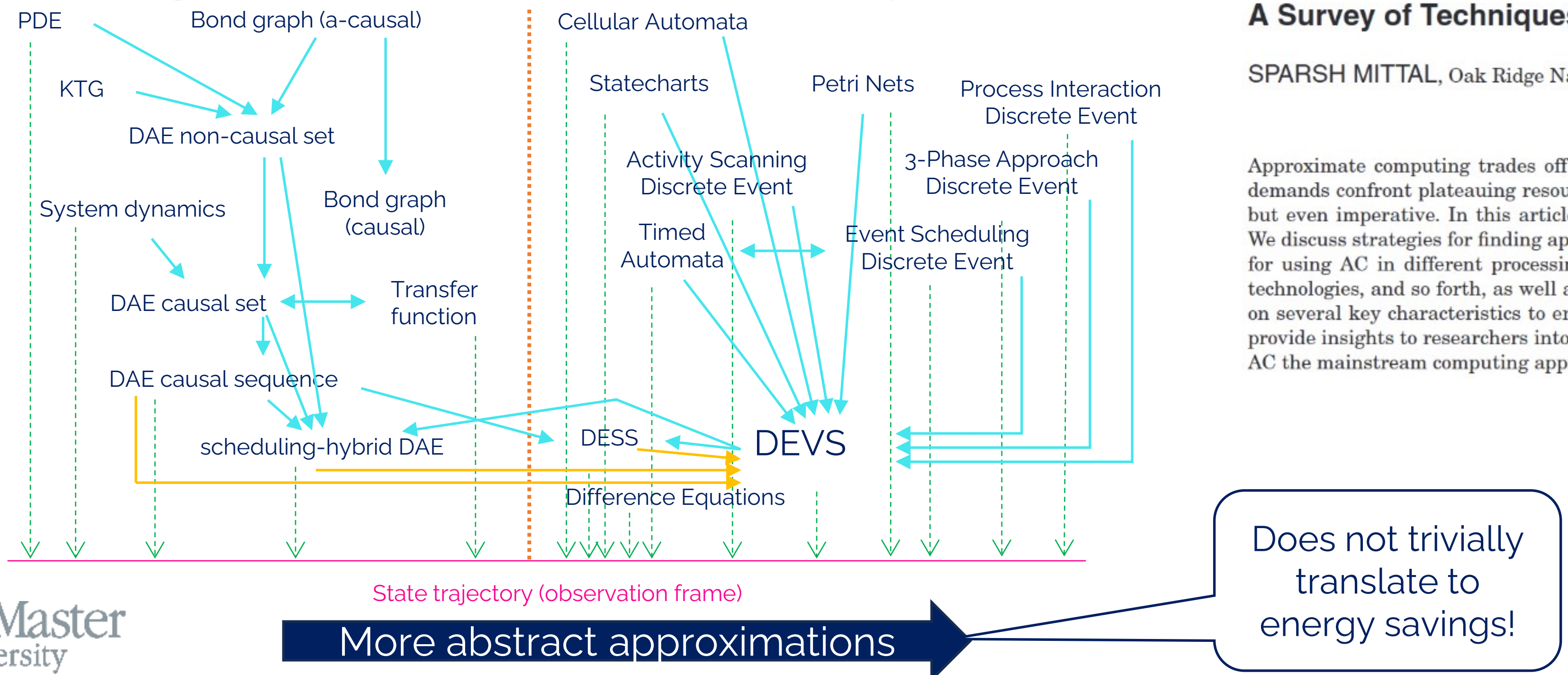
- Adoptability and human values
- Simulator inference
- DT evolution
- Energy-efficient DTs

-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







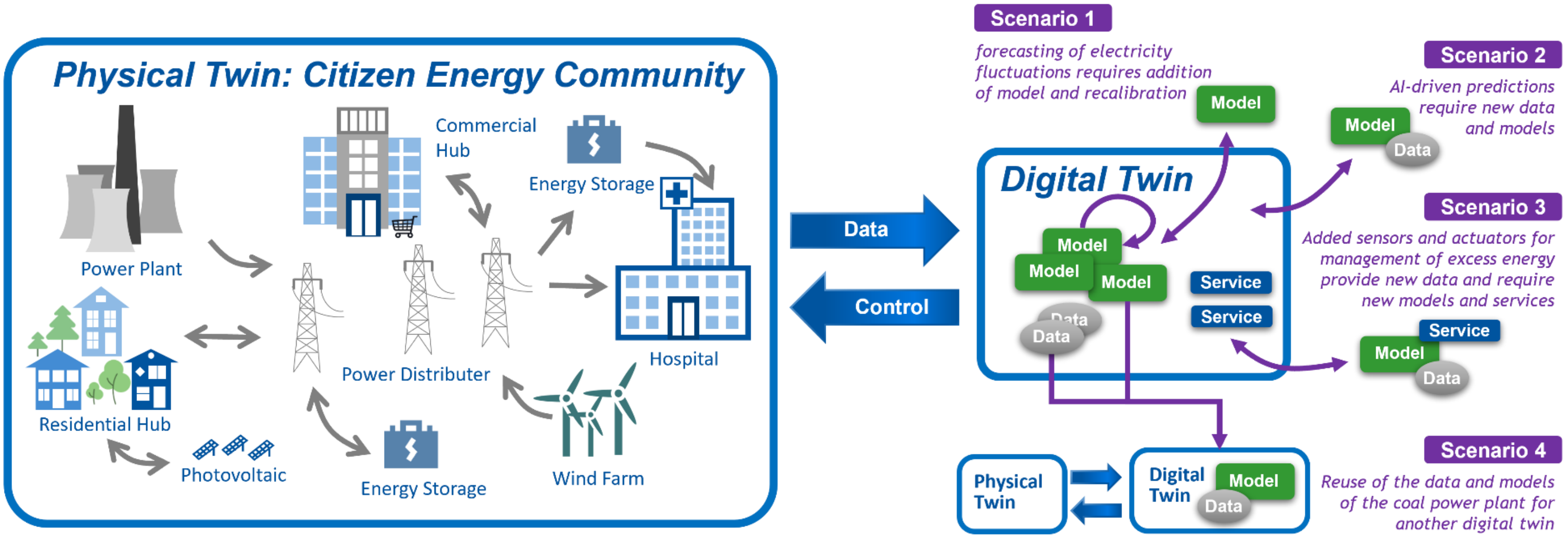
A Survey of Techniques for Approximate Computing

SPARSH MITTAL, Oak Ridge National Laboratory

Approximate computing trades off computation quality with effort expended, and as rising performance demands confront plateauing resource budgets, approximate computing has become not merely attractive, but even imperative. In this article, we present a survey of techniques for approximate computing (AC). We discuss strategies for finding approximable program portions and monitoring output quality, techniques for using AC in different processing units (e.g., CPU, GPU, and FPGA), processor components, memory technologies, and so forth, as well as programming frameworks for AC. We classify these techniques based on several key characteristics to emphasize their similarities and differences. The aim of this article is to provide insights to researchers into working of AC techniques and inspire more efforts in this area to make AC the mainstream computing approach in future systems.

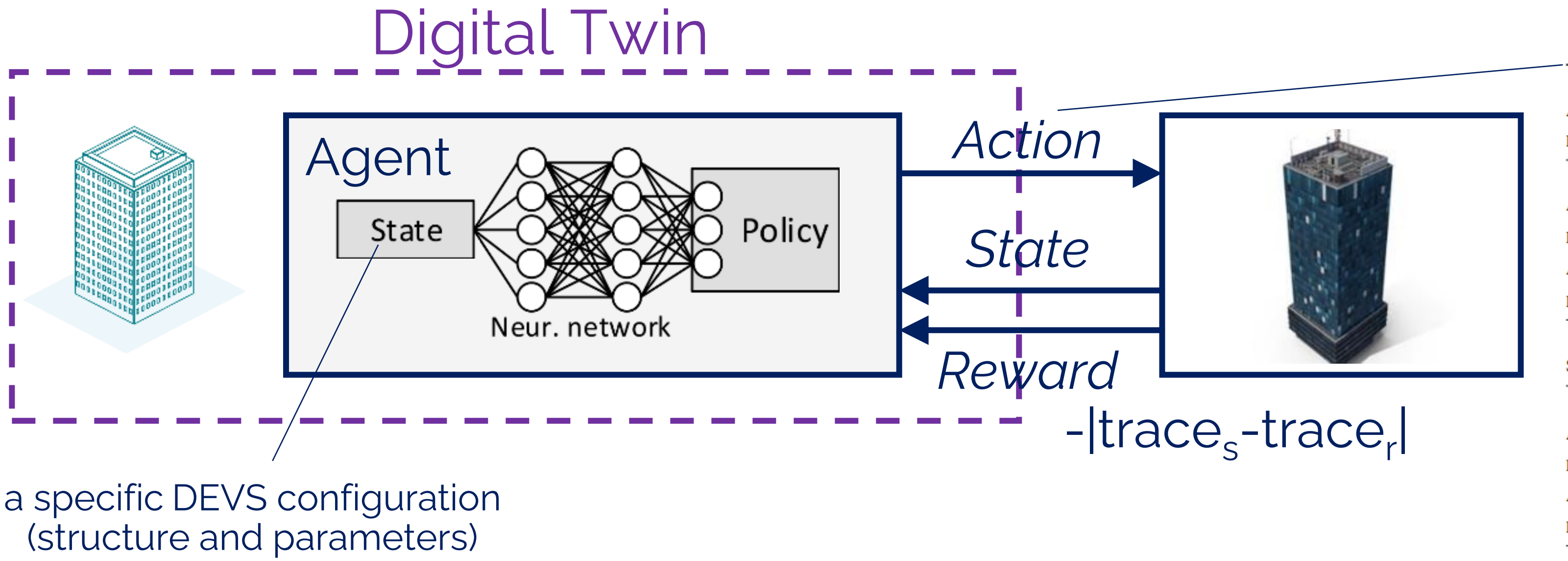
McMaster University

Evolution of Digital Twins



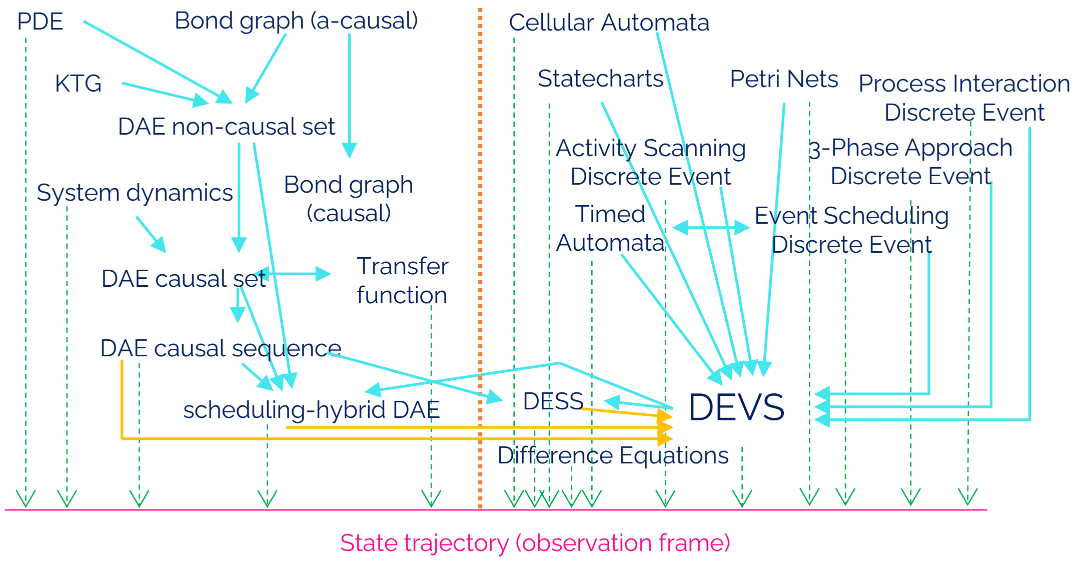
- Istvan David and Dominik Bork. "Towards a Taxonomy of Digital Twin Evolution for Technical Sustainability". In: MODELS-C 2023 Companion, Vasteras, Sweden. IEEE, 2023
- Judith Michael, Istvan David, and Dominik Bork. "Digital Twin Evolution for Sustainable Smart Ecosystems". In: MODELS-C 2024 Companion,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

Rapid development of Digital Twins: Simulator inference by reinforcement learning



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)

...



- 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.

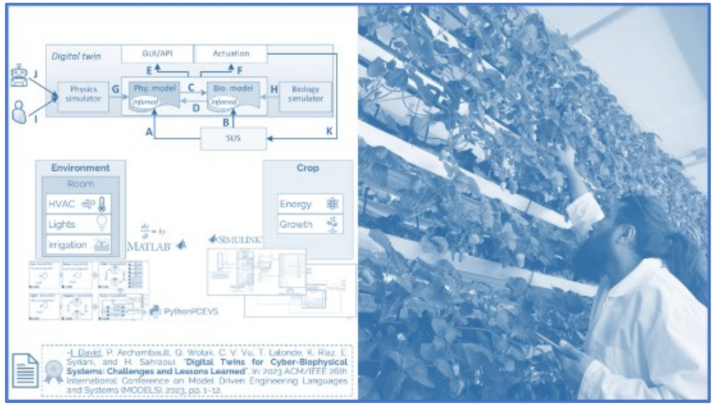
Tzachor, A., Sabri, S., Richards, C.E. *et al.* Potential and limitations of digital twins to achieve the Sustainable Development Goals. *Nat Sustain* **5**, 822–829 (2022). https://doi.org/10.1038/s41893-022-00923-7

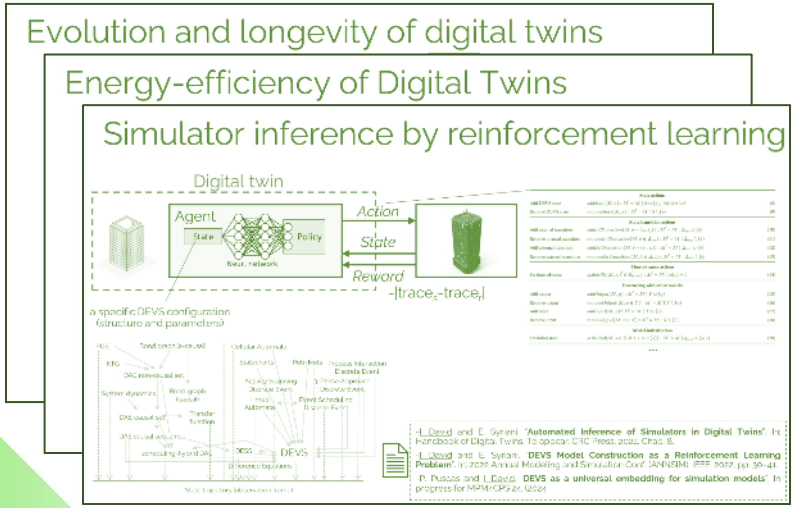
We need to engineer sustainable systems.
By sustainable methods.

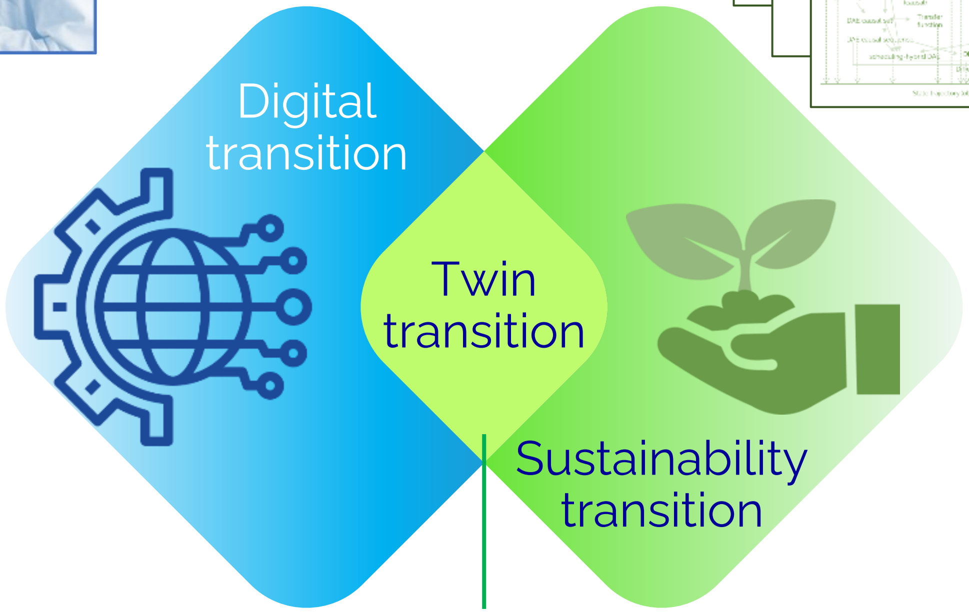
Sure. But how?

Sustainable systems

…by sustainable methods







Sustainability *of and by* digital tech

Sustainable Systems and Methods

Baran Shajari

McMaster University

Problem: social sustainability is missing from TT

- Social sustainability?
  - Trust in digitalization, transparency, explainability…
- Ignoring social sustainability leads to unwanted consequences
  - Unskilled workforce, fear of AI (e.g., losing jobs)
- HCI as the universal design framework in support of social sustainability of digital tech
  - Human-centered design, trust
  - Accessibility
  - Transparency

Bridging the Silos of Digitalization and Sustainability by Twin Transition: A Multivocal Literature Review

Baran Shajari*, Istvan David*,†

*McMaster University, Canada – {shajarib, istvan.david}@mcmaster.ca

†McMaster Centre for Software Certification (McSCert), Canada

***Abstract*—Twin transition is the method of parallel digital and sustainability transitions in a mutually supporting way or, in common terms, "greening of and by IT and data". Twin transition reacts to the growing problem of unsustainable digitalization, particularly in the ecological sense. Ignoring this problem will eventually limit the digital adeptness of society and the problem-solving capacity of humankind. Information systems engineering must find ways to support twin transition journeys through its substantial body of knowledge, methods, and techniques. To this end, we systematically survey the academic and gray literature on twin transition, clarify key concepts, and derive leads for researchers and practitioners to steer their innovation efforts.**

***Index Terms*—digital transformation, multivocal literature review, sustainability**

I. Introduction

Digital transformation has become an essential tool for companies to improve their operational excellence [39]. I… digitalization enables an array of competitive advanta… cluding enhanced data collection and management, qu… provements to products and services, and cost reducti…

Unfortunately, the benefits of improved digitalizati… at the price of increased environmental footprint [P3… mation and Communications Technology (ICT) curre… tributes to about 2-4% of global CO_2 emissions—co… to the carbon emissions of the avionics sector—… number is projected to increase to about 14% by 20… due to computation-heavy digital enablers, such as… big data. This growth is unsustainable. To follow … the rest of the economy, the ICT sector should—di… indirectly—decrease its CO_2 emissions by 42% by 20… by 2040, and 91% by 2050 [34]. Recently, compan… become more cognizant of the value of becoming … mentally sustainable, and the ways digitalization can … ambitions [4]. While digitalization exerts increasingl… environmental pressure, it also opens opportunities i… standing, assessing, and enforcing sustainability imp… e.g., through targeted data collection and process o… tion [19]. Sustainability and digitalization seem to be … dependent and inextricably linked [24]. This pose… challenges for companies that strive to be competi… (environmentally and socially) responsible at the sa… Pursuing such joint innovation agendas requires novel … to strike a balance between green and digital transitio…

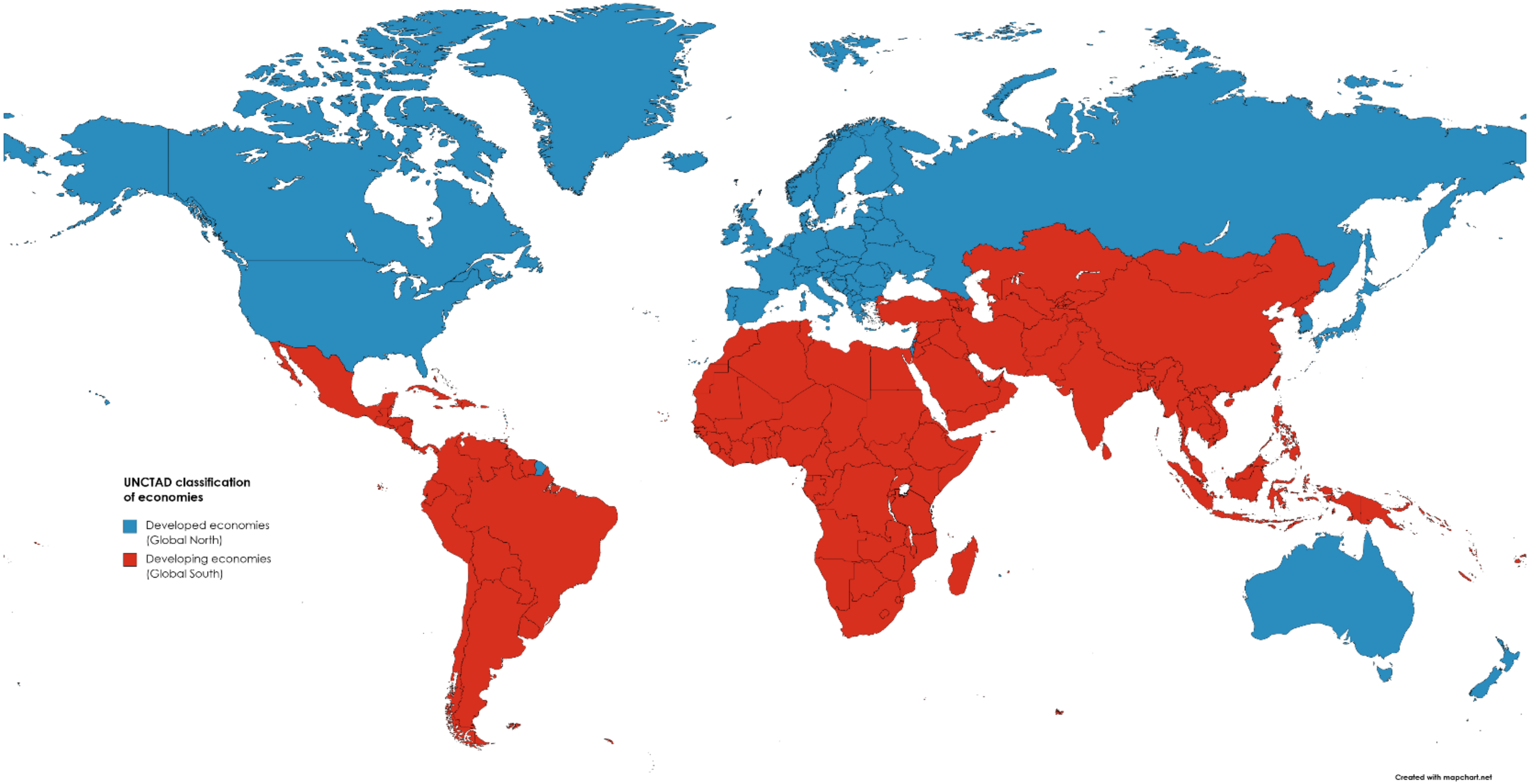
Originally suggested in the European Green Deal [36], twin transition is the paradigm of "*greening of and by IT& data*" [17], i.e., the fostering mutually reinforcing relationships between digital and sustainability transitions. As such, twin transition helps **bridge the silos of digitalization and sustainability**. While its benefits are clear, the concept of twin transition is not well-understood currently, and supporting methods are in their infancy.

Contributions

To understand the correct notions, enablers, and challenges of twin transition, we conduct a systematic literature review and elicit actionable leads for information systems researchers. Motivated by the early stage of research and limited academic literature, we opt for a multivocal study [30], i.e., we include non-academic ("gray") literature in our study, e.g., pre-prints

Baran Shajari

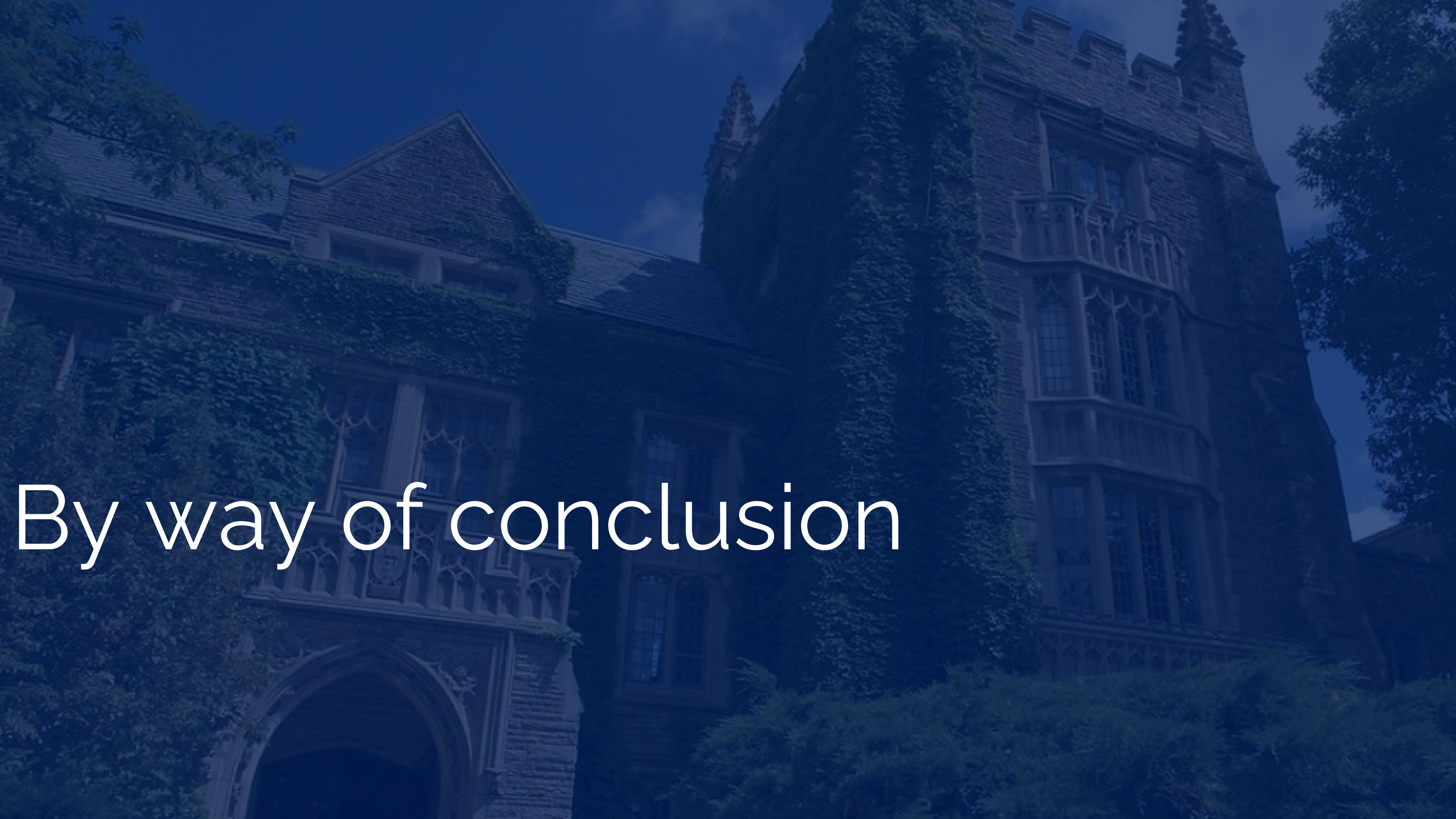
Societal divides



Digitalization can, in fact, widen the gap between developed and developing countries

McMaster University

By way of conclusion



Engineering complex and sustainable systems through digital twins