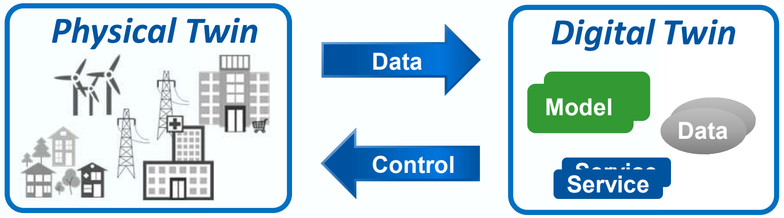

Digital Twin Evolution for Sustainable Smart Ecosystems

17th Int. Workshop on Models and Evolution (ME'24)

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27th International Conference on Model Driven Engineering Languages and Systems
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Linz, Austria

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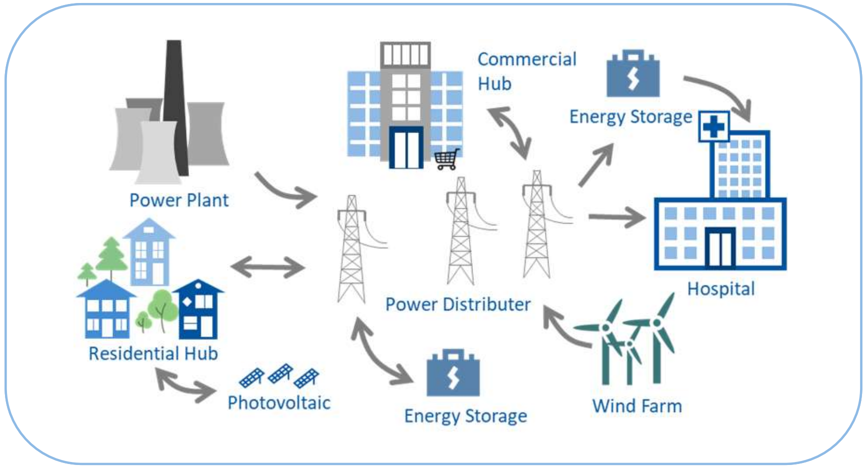
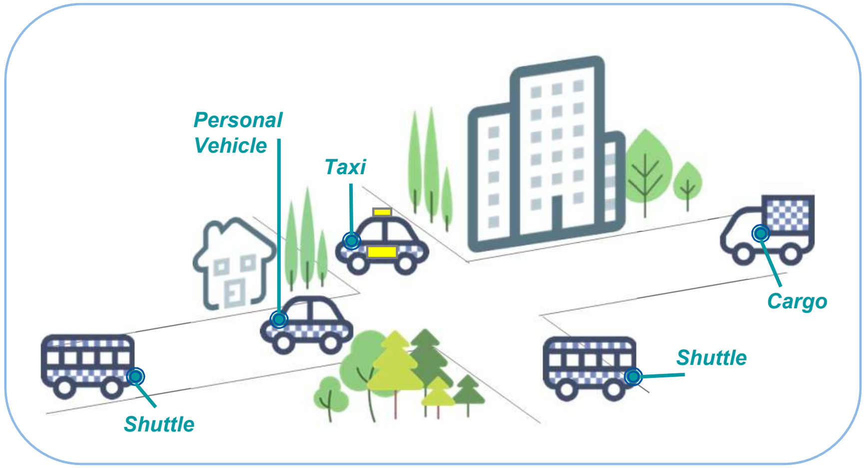
Software Engineering | RWTH AACHEN UNIVERSITY | McMaster University | TECHNISCHE UNIVERSITÄT WIEN Vienna University of Technology

Motivation | Smart Ecosystem Evolution

- *Smart Ecosystems*
  - *aim: ensure stable and sustainable operation*
  - Digital Twins to monitor, analyze, improve
  - evolve DTs in reaction to changing conditions
- *Evolution challenges*
  - software evolution is difficult to apply to DT evolution
  - intertwined physical and software components
  - individual evolution



Energy Systems



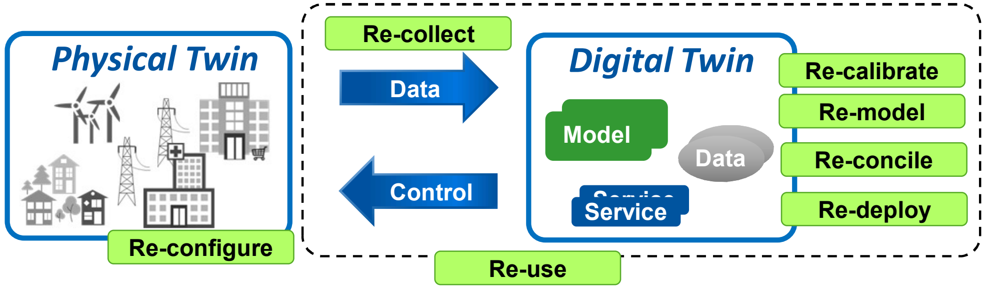
Transport Systems

Presentation topics

- 7R taxonomy of DT evolution
- citizen energy community case
- 4 DT evolution scenarios
- roles of software engineers in DT evolution
- organizational processes

The 7R Taxonomy of Digital Twin Evolution

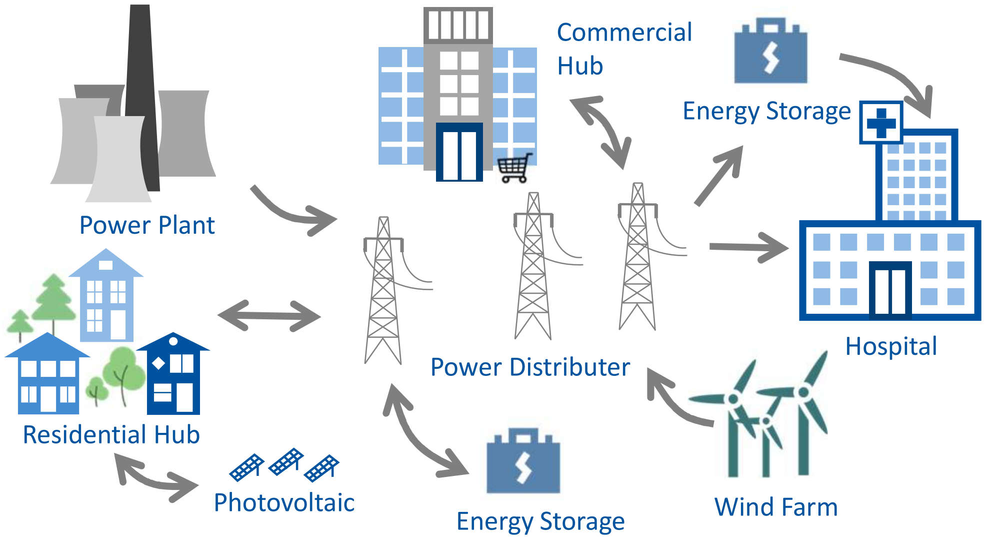
- **Re-calibration** of model parameters
  - model is not a faithful representation of the physical twin anymore
- **Re-modeling** the physical twin
  - model does not reflect the real phenomenon properly
  - specific software engineering tasks as refinements, e.g., re-architecting, re-packaging a software component
- **Reconciliation** of data
  - i.e., updating the data schema and migrating data
- **Re-collecting** data
  - events are missed due to transient errors
  - might necessitate reconciliation, re-modeling, and re-calibration



- **Re-deploying** the evolved digital twin
  - after at least one of the previous steps has been taken
- **Re-configuration** of the physical twin
  - when the physical twin evolves, and not operate under optimal circumstances
- **Reuse** of data, knowledge, and know-how
  - ensuring cost-efficient DT projects

[DB23] I. David, D. Bork: Towards a Taxonomy of Digital Twin Evolution for Technical Sustainability. In: ME Workshop @ MODELS, IEEE, 2023. https://doi.org/10.1109/MODELS-C59198.2023.00147

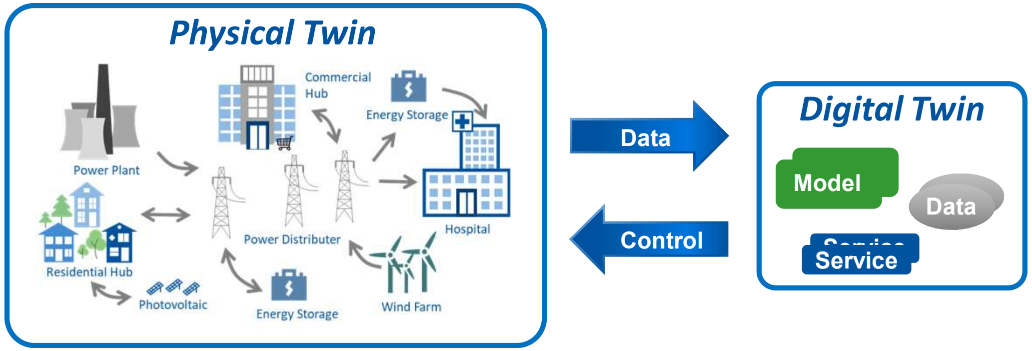
Citizen Energy Communities



- established at a local level
  - purpose to generate, distribute, supply, consume, aggregate, and store energy
- consist of entities consuming and producing energy
  - citizens, their buildings, small commercial or public entities
- enable local energy trading

[GKM+23] G. Gramelsberger, H. Kausch, J. Michael, F. Piller, F. Ponci, A. Praktiknjo, B. Rumpe, R. Sota, S. Venghaus: Enabling Informed Sustainability Decisions: Sustainability Assessment in Iterative System Modeling. In: ME Workshop @ MODELS, IEEE, 2023. https://doi.org/10.1109/MODELS-C59198.2023.00151

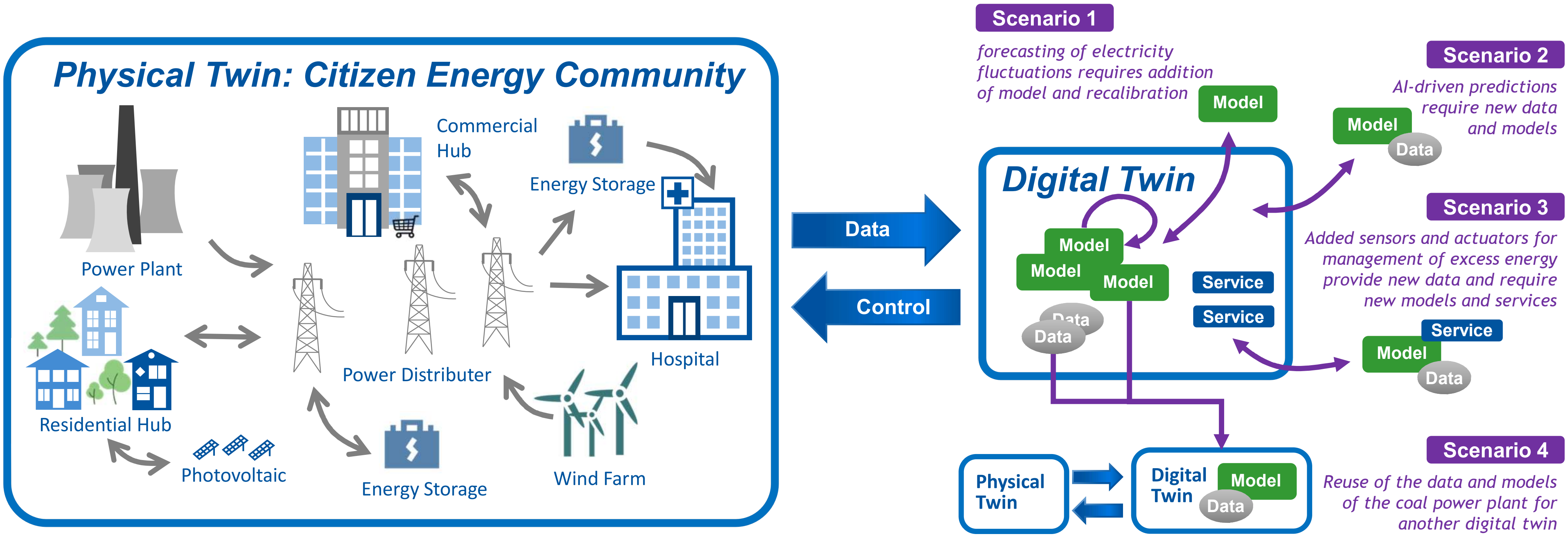
Citizen Energy Communities | Their Digital Twin



Services

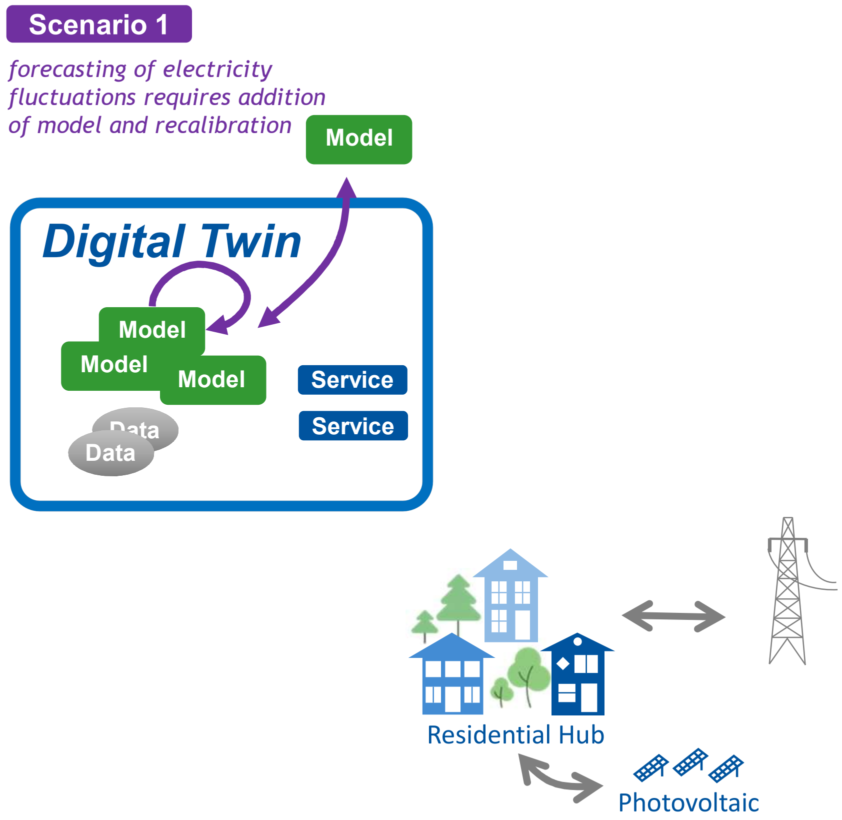
- *assessment* of different indicators
  - e.g., for sustainability, maintainability, or reusability
- support *improvement and evolvement* of (cyber-physical) systems within this ecosystem
- *monitor and optimize* the *energy trading* process
- *simulation of different energy provision* and *usage* scenarios
- *detect* when sensor information is incorrect
- *predictive maintenance*
  - of power lines, energy storages, or other physical components

4 DT Evolution Scenarios



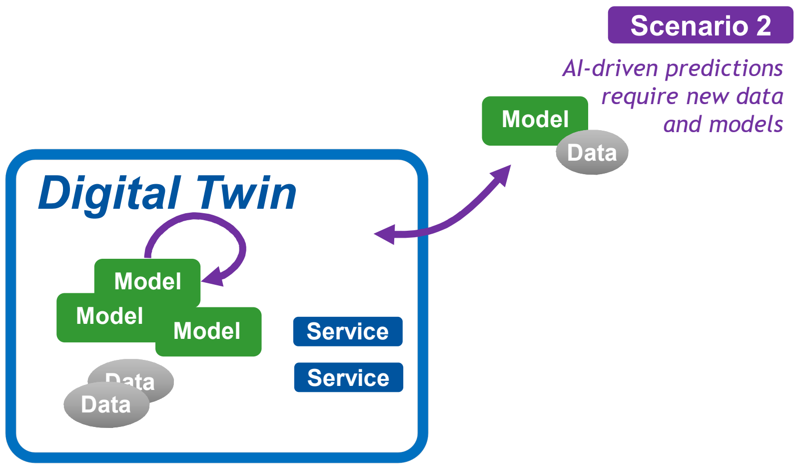
Scenario 1 | From a monitoring DT to a predictive DT

- residents, who *provide excess energy of photovoltaic systems* within citizen energy community network gets *financial incentives* from local government
  - client end-points also *produce* electricity
  - necessitates accurate forecasting of electricity fluctuations, especially excess electricity to prevent damage, e.g., due to overheating components
- Re-model *the electrical grid*
  - leveraging laws of physics: models of thermodynamics and external factors, e.g., atmospheric pressure and relative humidity
- Re-calibrate
  - because of new models
  - without calibration, models would not match the real system, resulting in inaccurate forecasts
  - calibration by manual tuning based on operational data collected by the DT



Scenario 2 | AI-driven predictions

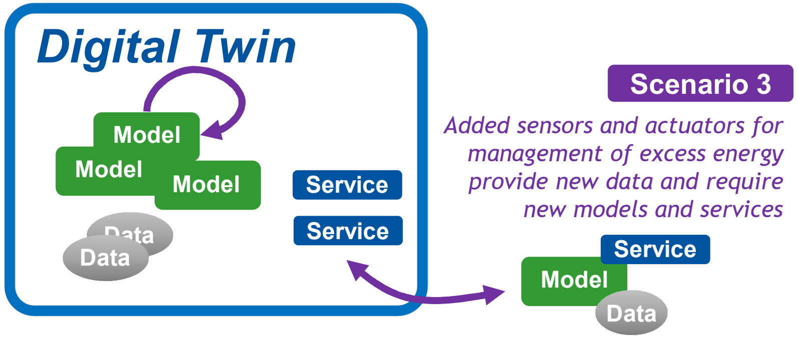
- grid operator decides to *improve DT predictive capabilities*
  - engineering model-based techniques require too much computing power for detailed simulations
  - AI-based predictive methods are realized
- Re-collect data
  - large volumes of data for new AI model, incl. new data
  - data points excluded from manually-built engineering models become interesting, e.g., environmental data such as cloud cover.
  - revisit data collection strategy
- Reconcile data management infrastructure
  - with newly collected data
    - e.g., updating data schemas and processing scripts;
    - addressing the organizational or legal framework when working with personal or sensitive data
- Re-model
  - generate AI-based prediction models trained on data from new data pipelines
- Re-calibrate
  - the model to adjust it to the evolved (i.e., extended) scope



Scenario 3 | Management of excess energy

- *equip the grid with the latest generation of safety components* against too much energy and resulting voltage frequency disturbances
  - sensors that detect potentially hazardous patterns
  - actuators that can act upon hazardous situations
  - DT operates these components

- Re-configure physical infrastructure
  - new sensors and actuators
- Re-collect
  - collect new data points, e.g., voltage frequency disturbance or energy overload in specific areas of the grid
- Re-model
  - new model reinforcement learning model
- Re-calibrate new model
- Re-deploy
  - visualize data from added sensors and actuators and results of the developed reinforcement learning approach



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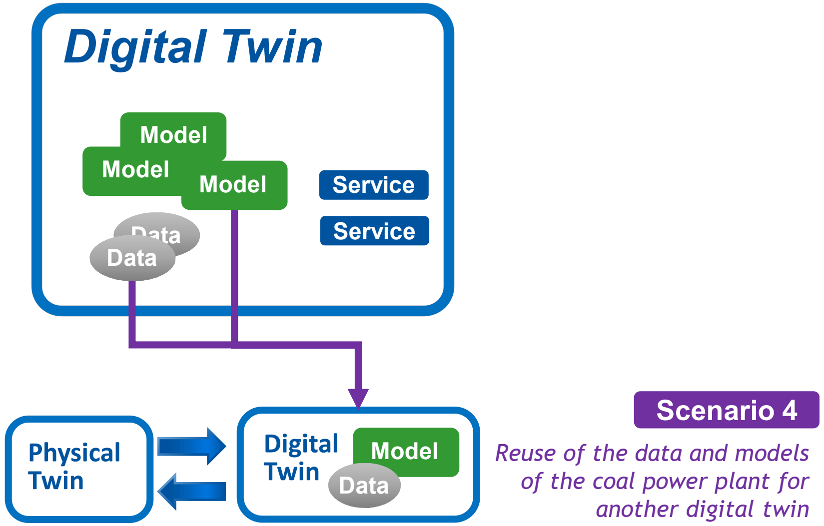
Scenario 4 | Retiring the coal power plant

- central coal power plant component is *not needed anymore*
  - distributed citizen energy community reach the level of self-sustainability, efficiency, and safety
  - political trends drive the obsolescence of coal-fired power generation

- *keep the DT*
  - DT is a source of important information
  - legal constraints require the grid operator to keep this data for several years

- Reuse
  - e.g., design documents, design rationale (engineering decisions), experimental simulation traces, operative information collected by the DT
  - effective reuse requires further actions, e.g., re-calibrating models or re-collecting additional data

  - *resource value retention*, e.g., reusing particular components of a power plant, repairing or replacing parts in the smart grid, or re-purposing buildings



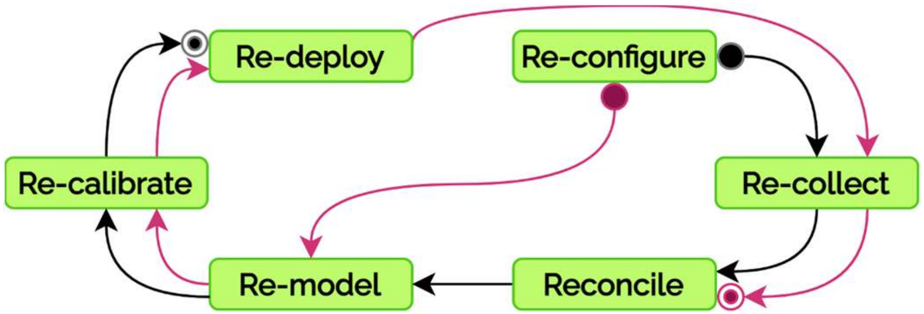
Software Engineers: Involvement

R-imperative	Involvement of software engineers Primary role	Extent
Re-calibrate	Update models. In major cases: support model engineers and scientists.	◑
Re-model	Support model engineers and scientists, and refactor models for scalability.	◔
Re-collect	Integration with sensor APIs and middleware (e.g., messaging).	◕
Reconcile	Maintenance of data management pipelines, ETL processes, data schemas.	◕
Re-deploy	Infrastructure-as-Code, DevOps, CI/CD.	●
Re-configure	Middleware development, embedded software development.	◑
Reuse	Software componentization for reuse. Transfer learning from AI components.	◔

◔ least software-intensive
◑ moderately software-intensive
◕ fairly software-intensive
● most software-intensive

Organizational Processes

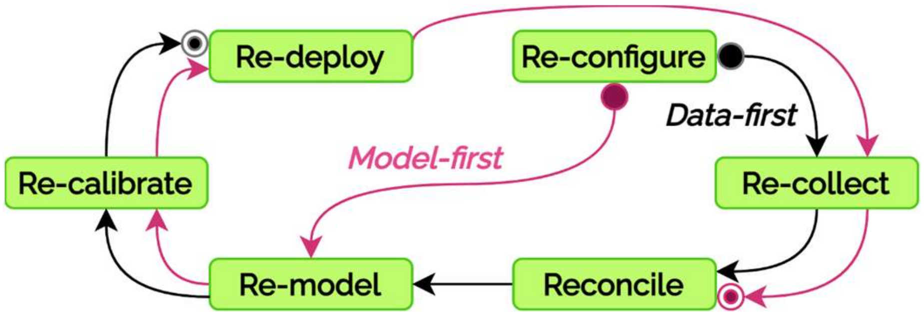
Different variants in realization



- ***Extent**: short versus long loops*
  - the shorter the loop, the easier to oversee and manage
  - *shorter loops*
    - on the digital side (i.e., touching upon re-modeling, re-calibration, and re-deployment)
    - more frequently within software engineering companies
  - *longer loops*
    - extend into other domains
    - require more elaborate cooperation

Organizational Processes

- ***Intent**: data-first versus model-first*
  - chain R-imperatives in a different order, with more cycles
  - preferred order of R-imperatives depends on company best practices and employed paradigms
  - *data-first approach:*
    - re-configure the PT, data collection, …
    - prevalent in practice
  - *model-first approach:*
    - re-configuration of the physical, re-modeling, …
    - benefit: models can be used to re-generate data schemas and processing scripts resulting in data collection with reduced manual intervention



- ***Vendor dependence***
  - software companies work with various vendors
  - equipment vendors ship devices coupled with models pre-configured with reasonable defaults
    - longer loops are to be expected

Summary and Discussion

Digital Twin Evolution for Sustainable Smart Ecosystems

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ABSTRACT

Smart ecosystems are the drivers of modern society. They control infrastructures of socio-techno-economic importance, ensuring their stable and sustainable operation. Smart ecosystems are governed by digital twins—real-time virtual representations of physical infrastructure. To support the open-ended and reactive traits of smart ecosystems, digital twins need to be able to evolve in reaction to changing conditions. However, digital twin evolution is challenged by the intertwined nature of physical and software components, and their individual evolution. As a consequence, software practitioners find a substantial body of knowledge on software evolution hard to apply in digital twin evolution scenarios and a lack of knowledge on the digital twin evolution itself. The aim of this paper, consequently, is to provide software practitioners with tangible leads toward understanding and managing the evolutionary concerns of digital twins. We use four distinct digital twin evolution scenarios, contextualized in a citizen energy community case to illustrate the usage of the 7R taxonomy of digital twin evolution. By that, we aim to bridge a significant gap in leveraging software engineering practices to develop robust smart ecosystems.

CCS CONCEPTS

• **Software and its engineering** → *Software evolution*; • **General and reference** → *Reference works*; • **Hardware** → *Smart grid*.

KEYWORDS

cyber-physical systems, digital twins, evolution, sustainability

ACM Reference Format:

Judith Michael, Istvan David, and Dominik Bork. 2024. Digital Twin Evolution for Sustainable Smart Ecosystems. 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, 5 pages. https://doi.org/10.1145/3652620.3688343

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1 INTRODUCTION

Our modern world runs by smart ecosystems—large-scale, decentralized systems, capable of self-organization and self-optimization [13]. Examples of smart ecosystems include smart cities [8], smart energy communities [9], and smart grids with renewable components [10].

Much like natural ecosystems, smart ecosystems are open-ended and need to allow for continuous changes in their structure and behavior. These evolutionary dynamics, in turn, challenge the technical sustainability [18] of smart ecosystems, i.e., their ability to maintain the quality of service over a prolonged period of time [12]. To improve the sustainability of smart ecosystems, proper evolution mechanisms are required to be put in place. While evolution has a substantial body of knowledge in model-driven software engineering [6, 11], hybrid cyber-physical components of smart ecosystems, such as digital twins [14], give rise to challenges traditional software engineering techniques fall short of addressing.

Digital twins are real-time, virtual representations of physical system components [14]. They govern smart ecosystems and provide essential mechanisms and services to assess, simulate, and control the physical infrastructure of smart ecosystems for optimal behavior [17]. Thus, to ensure the technical sustainability of smart ecosystems, first, the technical sustainability of digital twins must be managed. Changes in digital twins boil down to a heterogeneous set of components, including software, hardware, middleware, and IoT devices. The interdependency of concerns severely hinders the applicability of software engineering techniques and even challenges the very understanding of evolutionary needs.

To help software engineers apply their expertise in digital twin evolution scenarios, we provide a *case-based demonstration of the 7R taxonomy* in this paper. The 7R taxonomy of digital twin evolution [4] defines seven elementary activities to support the technical sustainability of digital twins.

This paper is structured as follows. In Sec. 2, we elaborate on a case of an evolving smart ecosystem, driven by digital twin evolution. In Sec. 3, we recommend action points to apply the 7R taxonomy. In Sec. 4, we draw the conclusions. We provide background information about key concepts in sidebars.

2 CASE: CITIZEN ENERGY COMMUNITY

To illustrate the usage of the 7R taxonomy (see sidebar), we rely on a practical case of an evolving smart ecosystem, called the citizen energy community.

Energy communities enable collective, citizen-driven energy actions to support a clean energy transition [2]. In citizen energy communities (Fig. 1), citizens and small commercial entities are equipped with *energy generation* and *storage capacity*, promoting them to first-class *generators of energy*. As opposed to traditional regulatory models, a citizen energy community gives rise to a *smart*

7R taxonomy of digital twin evolution fosters *better decisions* in a convoluted *problem space* in which *software engineers* are *key to success*

…more in the paper

Questions?

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