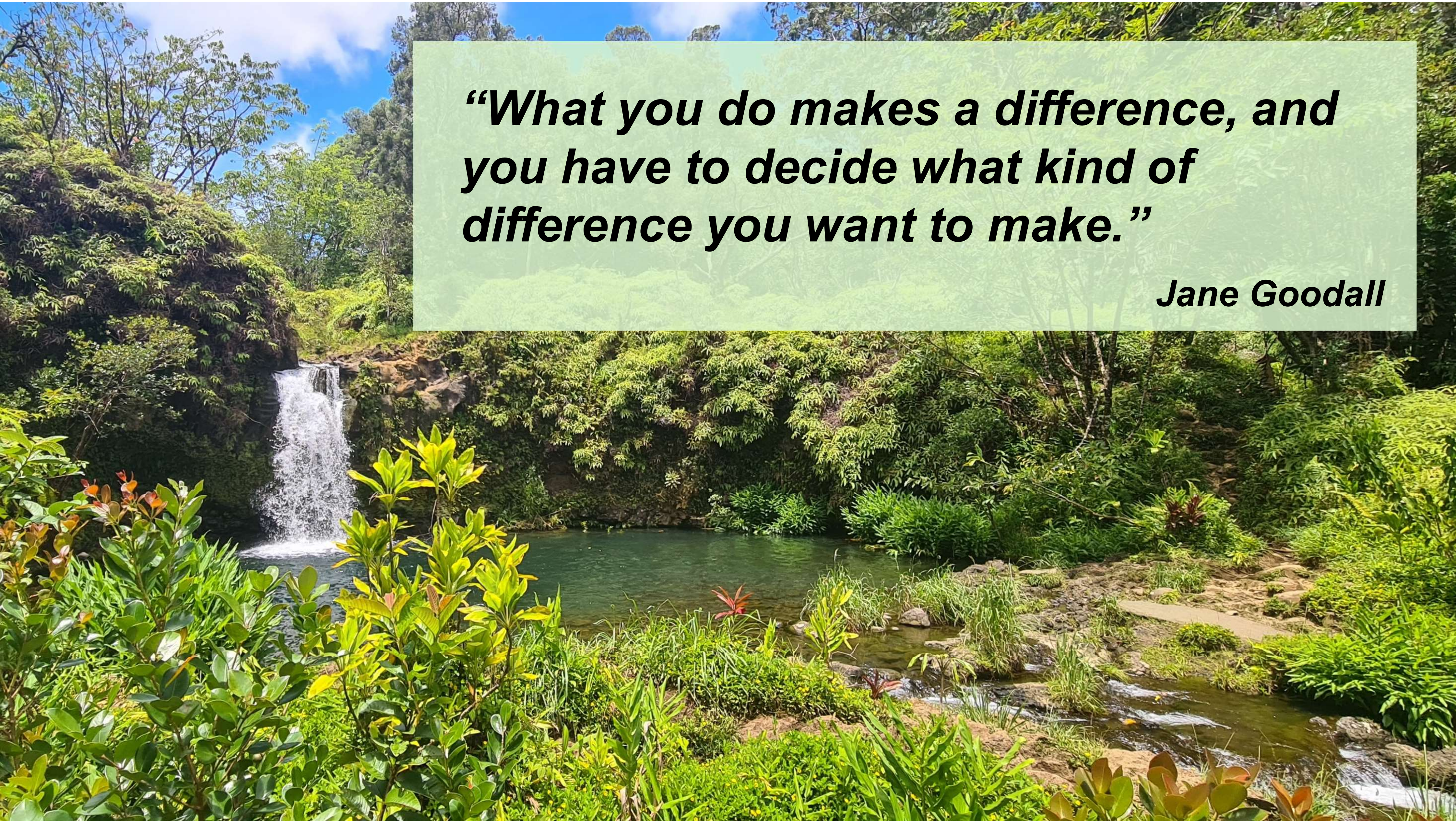
Towards Sustainable Systems: Paving the Way with Digital Twins

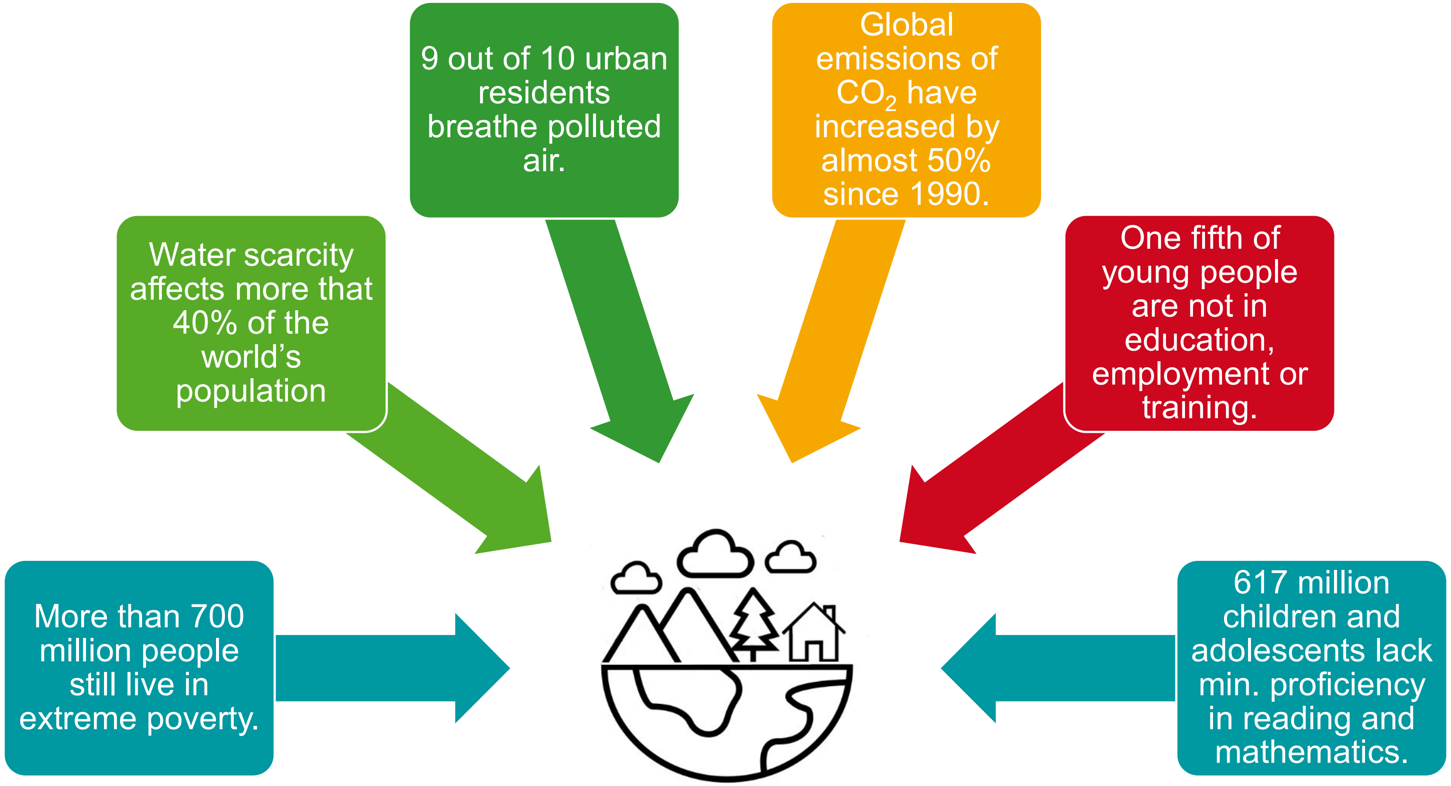
Judith Michael
Software Engineering
RWTH Aachen University

http://www.se-rwth.de

EDT Seminar Series
04.12.2023, Online


"What you do makes a difference, and you have to decide what kind of difference you want to make."
Jane Goodall

Real world challenges (some…)



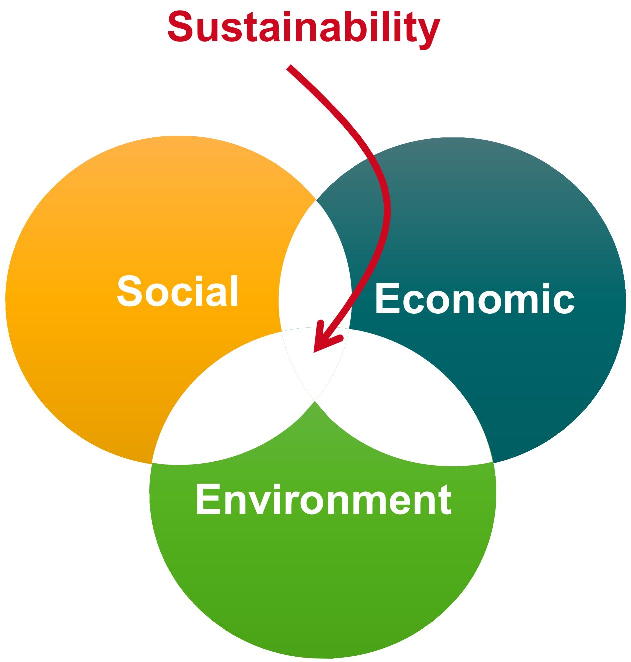
Source: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

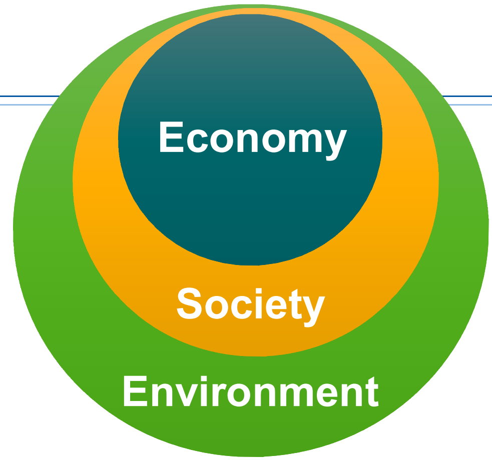
Should we really continue on this „highway to hell“?

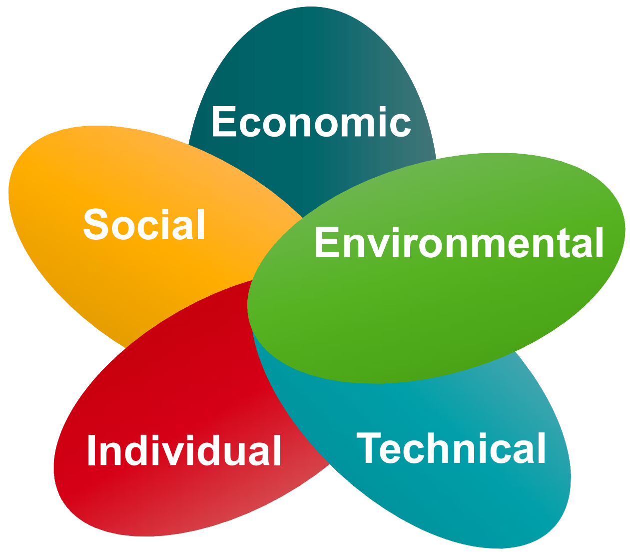

How can we from the EDT.community
contribute to a better world?

Sustainability

- Ecological Sustainability
  - preserve and protect the *natural environment* over time
  - *meet present needs* without compromising the *availability of resources* in the future
- Social Sustainability
  - focus on the *well-being of people* and communities
  - promoting equity, human rights, access to education and health care, and decent work
- Economic Sustainability
  - conduct *economic activities* in a way that *long-term economic well-being* is possible
  - balance between economic growth, resource efficiency, social equity, financial stability







B. Purvis, Y. Mao, and D. Robinson, “Three pillars of sustainability: In search of conceptual origins,” Sust. Science, vol. 14, no. 3, 2019.

UN Sustainable Development Goals

- 17 goals
  - 169 targets
  - measured by 231 indicators

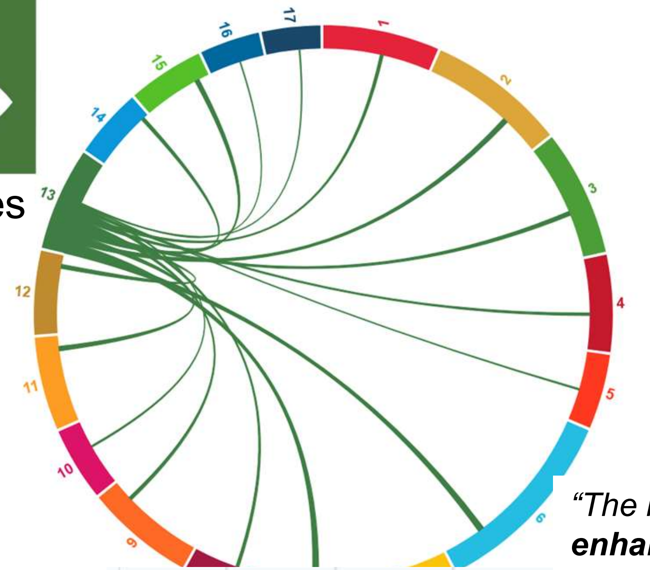
Example

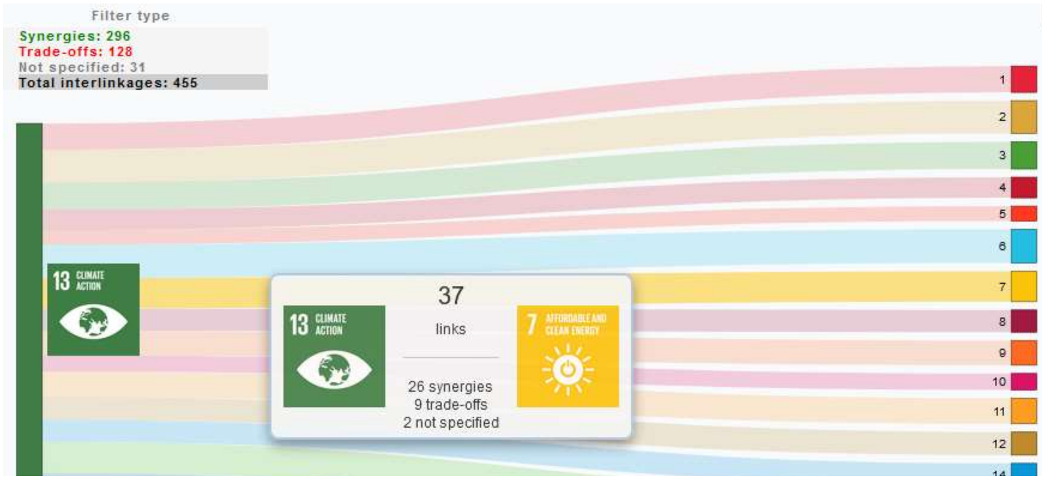
- SDG 7
  Affordable and clean energy
- 5 targets, e.g.,
  - *7.3 “By 2030, double the global rate of improvement in energy efficiency.”*
- 6 indicators, e.g.,
  - *7.3.1 “Energy intensity measured in terms of primary energy and GDP.”*

https://sdgs.un.org/goals

SDG Interlinkages | Synergies and Trade-Offs

Synergies





"The increase in diversity of (clean) energy sources and related infrastructure investments would ***enhance access*** *to modern energy services (here we defined all low-carbon energy sources as modern),* ***but energy affordability may be affected****."*

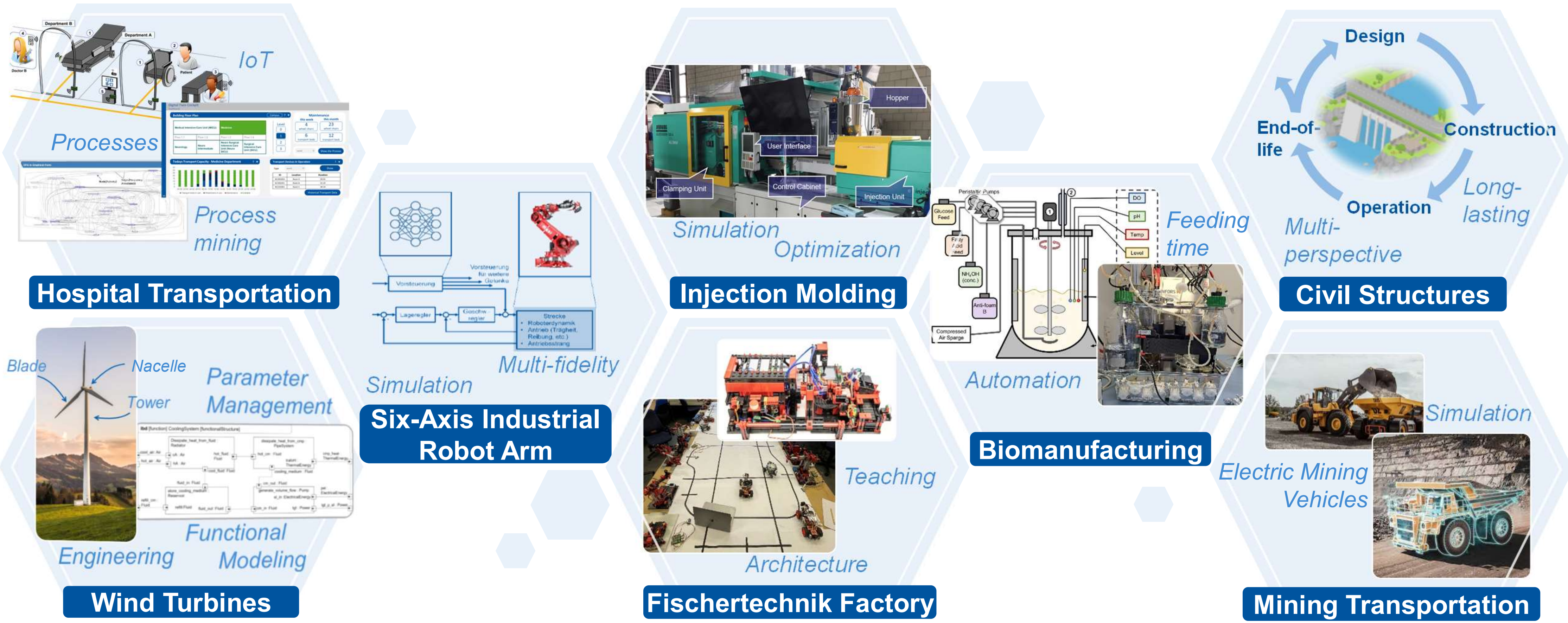
13	7	trade-off	yes	energy services (here we defined all low-carbon energy sources as modern), but energy affordability may be

Publication ID	Method type	Geographic scale	Geographic context	Year	Title	Authors	Link
Iacobuta_2021	Mixed (Literature review; Expert judgement)			2021	Transitioning to low-carbon economies under the 2030 agenda: Minimizing trade-offs and enhancing co-benefits of climate-change action for the sdgs	Iacobuţă G.I., Höhne N., van Soest H.L., Leemans R.	

Source: https://knowsdgs.jrc.ec.europa.eu/interlinkages-goals

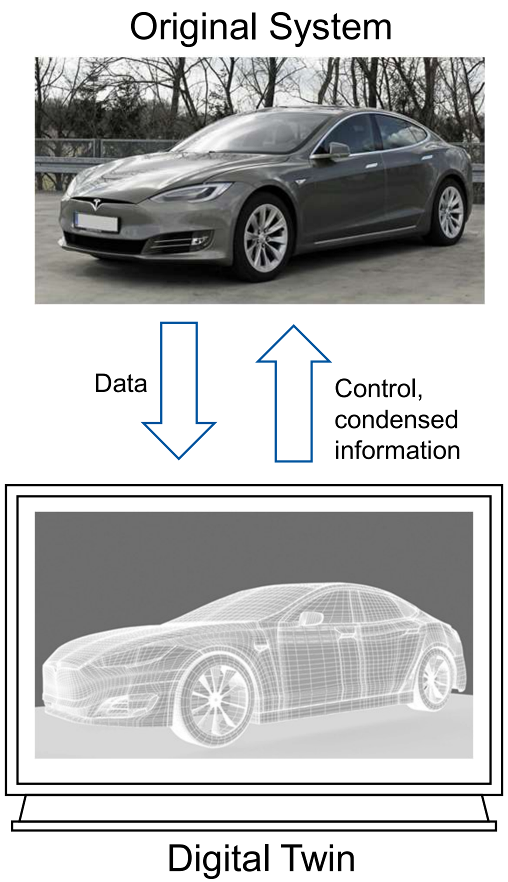
Digital Twins *of Cyber-Physical Systems*

Some Digital Twin Use Cases



Digital Twins *of Systems*

Digital Twins as *complex, long-lasting software systems*



contextual data and their aggregation and abstraction

A Digital Twin of a system consists of
- a set of models of the system and
- a set of digital shadows,
  - both of which are purposefully updated on a regular basis, and
- provides a set of services to use both purposefully with respect to the original system.

- The digital twin interacts with the original system by
  - providing useful information about the system's context and
  - sending it control commands.

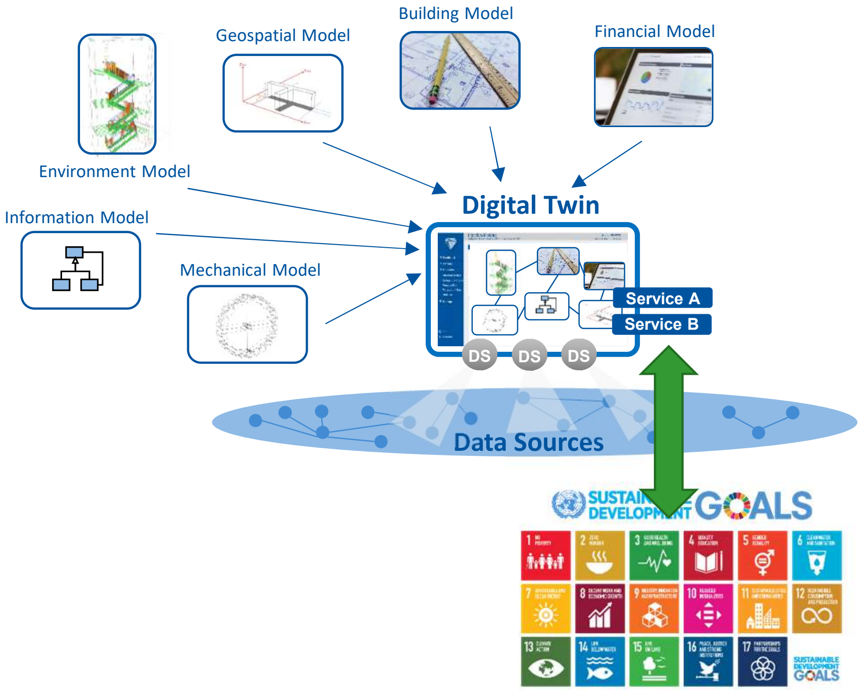

Digital Twins enable us
to connect reality with
the digital world
and back

HOW CAN WE **USE** DTS TO ASSESS THE SUSTAINABILITY OF COMPLEX SYSTEMS?

Digital Twins for Sustainability Assessment

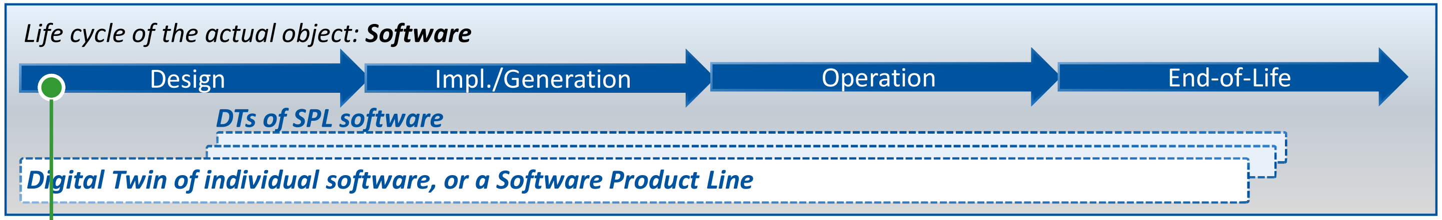
- Engineering DTs for *sustainability assessment*
  - assessment of sustainability *targets*
    - monitor, calculate and visualize key sustainability indicators
  - simulation and forecasting of sustainability indicators
    - use historic information together with forecasting algorithms

- DT services, e.g., in *production*, to
  - enable simulation of different *variants* of DTs before building the physical one to improve resource efficiency
  - facilitate optimizing *production* processes towards waste reduction and energy saving
  - provide self-adaptability to improve resource efficiency
  - assist with responsible consumption and use in relation to created products



17 UN development goals (SDGs) with 169 associated targets

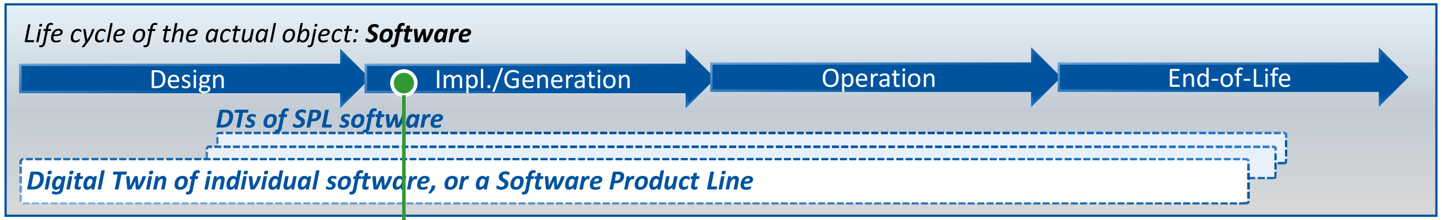
DT during *design* of a software system



- Services for **analysis of sustainability**
  - architecture model analysis, e.g., optimize consumed resources
  - scenario-based analysis, e.g., resource usage, identify resource-intensive parts
  - …

[HHMR23] M. Heithoff, A. Hellwig, J. Michael, B. Rumpe: Digital Twins for Sustainable Software Systems. GREENS'23 Workshop at ICSE'23

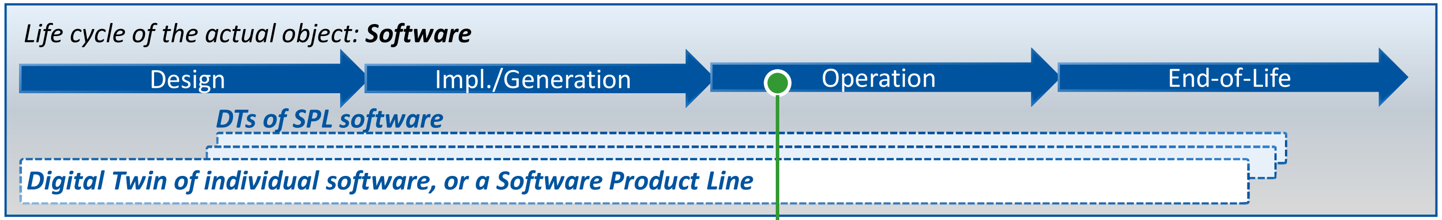
DT during *implementation/ generation* of a software system



- Creation of **digital shadows**
  - logs of execution sequences, data about resources usage, development processes in tools, source code metrics
- **Services** for
  - identification and optimization of resource-intensive code sections
  - analyzing the development process, e.g., identify least sustainable parts, bottlenecks
  - …

[HHMR23] M. Heithoff, A. Hellwig, J. Michael, B. Rumpe: Digital Twins for Sustainable Software Systems. GREENS'23 Workshop at ICSE'23

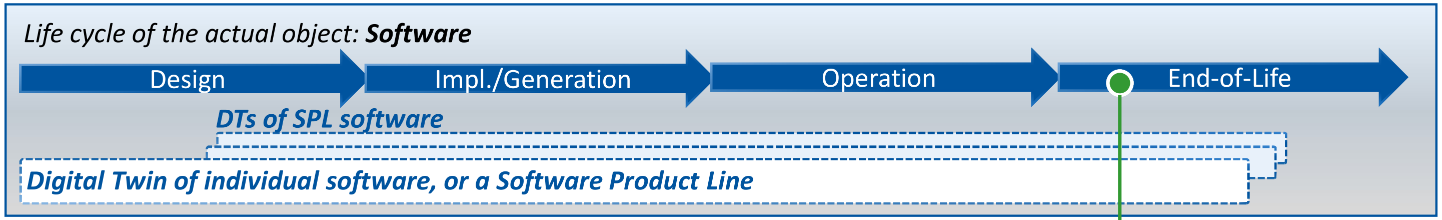
DT during *operation* of a software system



- Creation of **digital shadows**
  - runtime data of the software system
- **Monitor & report**
- **Analyze** sustainable operation & energy peaks
- **Optimize** & **intervene** in the software system
  - allocating resource adjusted to the current needs, reconfiguring system parameters, cleanups to guarantee durability
- …

[HHMR23] M. Heithoff, A. Hellwig, J. Michael, B. Rumpe: Digital Twins for Sustainable Software Systems. GREENS'23 Workshop at ICSE'23

DT during *end-of-life* of a software system



- Draw conclusions about a **component's relevance and reliability** in **future software systems**
  - compare planned behavior in design with actual behavior in operation (e.g., process conformance, analyses on error logs)
  - compare logged energy consumption with energy goals
  - identify integration problems by analyzing test reports
- …

[HHMR23] M. Heithoff, A. Hellwig, J. Michael, B. Rumpe: Digital Twins for Sustainable Software Systems. GREENS'23 Workshop at ICSE'23

Paper: Digital Twins for Sustainable Software Systems

Digital Twins for Sustainable Software Systems

Malte Heithoff, Software Engineering, RWTH Aachen University, Aachen, Germany, heithoff@se-rwth.de
Alexander Hellwig, Software Engineering, RWTH Aachen University, Aachen, Germany, hellwig@se-rwth.de
Judith Michael, Software Engineering, RWTH Aachen University, Aachen, Germany, michael@se-rwth.de
Bernhard Rumpe, Software Engineering, RWTH Aachen University, Aachen, Germany, rumpe@se-rwth.de

***Abstract*—Sustainable software systems aim to create resource-efficient software products and reduce the carbon impact of applications. Current approaches for sustainability assessment of software are either only focused on their operation or rely on methods in their engineering. More holistic approaches for sustainable software system spanning are missing. Thus, we are interested in the engineering of sustainable software systems together with the monitoring of their sustainability goals over their whole lifetime. Within this paper, we suggest using digital twins to accompany software systems in all life cycle phases with a specific focus on using model-driven engineering methods for the creation of applications. We can generate accompanying digital twins which share relevant models and data with the actual system and provide services for the assessment of sustainability indicators. In the long run, this provides us with better assessment options for software systems.**

***Index Terms*—Model-Driven Engineering, Digital Twins, Sustainable Software Systems**

I. INTRODUCTION

When technical developments are considered in terms of their social, economic, and environmental aspects of sustainability [1], they should have a positive impact on our world. To assess this impact, the United Nations have developed 17 sustainable development goals (SDGs) with 169 associated targets [2] we should achieve. Assessing software systems [3] based on these targets requires manual effort as one has to evaluate various aspects and take data from heterogeneous data sources into account. Up to now, sustainability assessment of software systems is often a manual task. One has to manually assess different sustainability criteria [4], e.g., with scenario-based techniques [5], and continuously update the assessment in case of changes in the software.

Our aim is to investigate how to create sustainable software systems with Model-Driven Engineering (MDE) methods and monitor the sustainability goals of these synthesized systems.

We suggest using Digital Twins (DTs) to accompany software systems in all life cycle phases to reach this goal. Up to now, digital twins are mainly used to accompany Cyber-Physical Systems (CPSs), e.g., airplanes [6], cars [7], wind turbines [8], machine elements [9], injection molding machines [10], or buildings [11]. The experiences made at DT engineering for CPSs [12] can be transferred to DTs for software systems created using MDE methods. We discuss the life cycle of software systems, relevant aspects for sustainability assessment, and how MDE methods support the engineering of their DTs.

The paper is structured the following: Section II provides foundations and related work. Section III presents our vision on how to use digital twins for sustainability assessment and discusses it, and the last section concludes.

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC 2023 Internet of Production - 390621612. Website: https://www.iop.rwth-aachen.de

II. FOUNDATIONS AND RELATED WORK

Whereas the General Assembly of the United Nations provides us with concrete 17 SDGs with 169 associated targets [2], translating these goals to software systems is still a challenge. Penzenstadler [13] defines sustainability "as preserving the function of a system over a defined time span" requiring to define the three variables system, function, and time. These can be defined in software engineering from four perspectives:

- Development processes: This includes software engineering processes with responsible use of ecological, human, and financial resources.
- Software maintenance: This includes the maintenance and evolvement of a software system with minimized environmental impact, well-managed knowledge, and sufficient economic balance.
- System production: In this perspective, the software is considered a concrete product including its hardware and the resources needed for production.
- System usage: Here, we take the entire period of use of the software and its operational environment into account.

There exists a large variety of metrics to assess green software [14]. Venters et al. [3] suggest considering software sustainability as a non-functional requirement. Measuring the extensibility, interoperability, maintainability, portability, reusability, scalability, and usability of a system enables us to make statements about its sustainability. This allows analyzing, evaluating, and reasoning about sustainability at an architectural level [15]. Kern et al. [4] describe causal chains from software products to their impacts on natural resources, e.g., energy. Design choices in software engineering, e.g., which programming language to use, compiler optimization, and implementation choices, have an influence on the energy efficiency of programs [16].

Digital Twins. We suggest using DTs to accompany software systems in all life cycle phases to support their sustainability

Digital Twins of software systems to support the sustainability assessment of applications

- …more in the paper

- Further research
  - How to model sustainability metrics?
  - What services are helpful for developers?

To the
Paper
se-rwth.de/publications

[HHMR23] M. Heithoff, A. Hellwig, J. Michael, B. Rumpe: Digital Twins for Sustainable Software Systems. GREENS'23 Workshop at ICSE'23

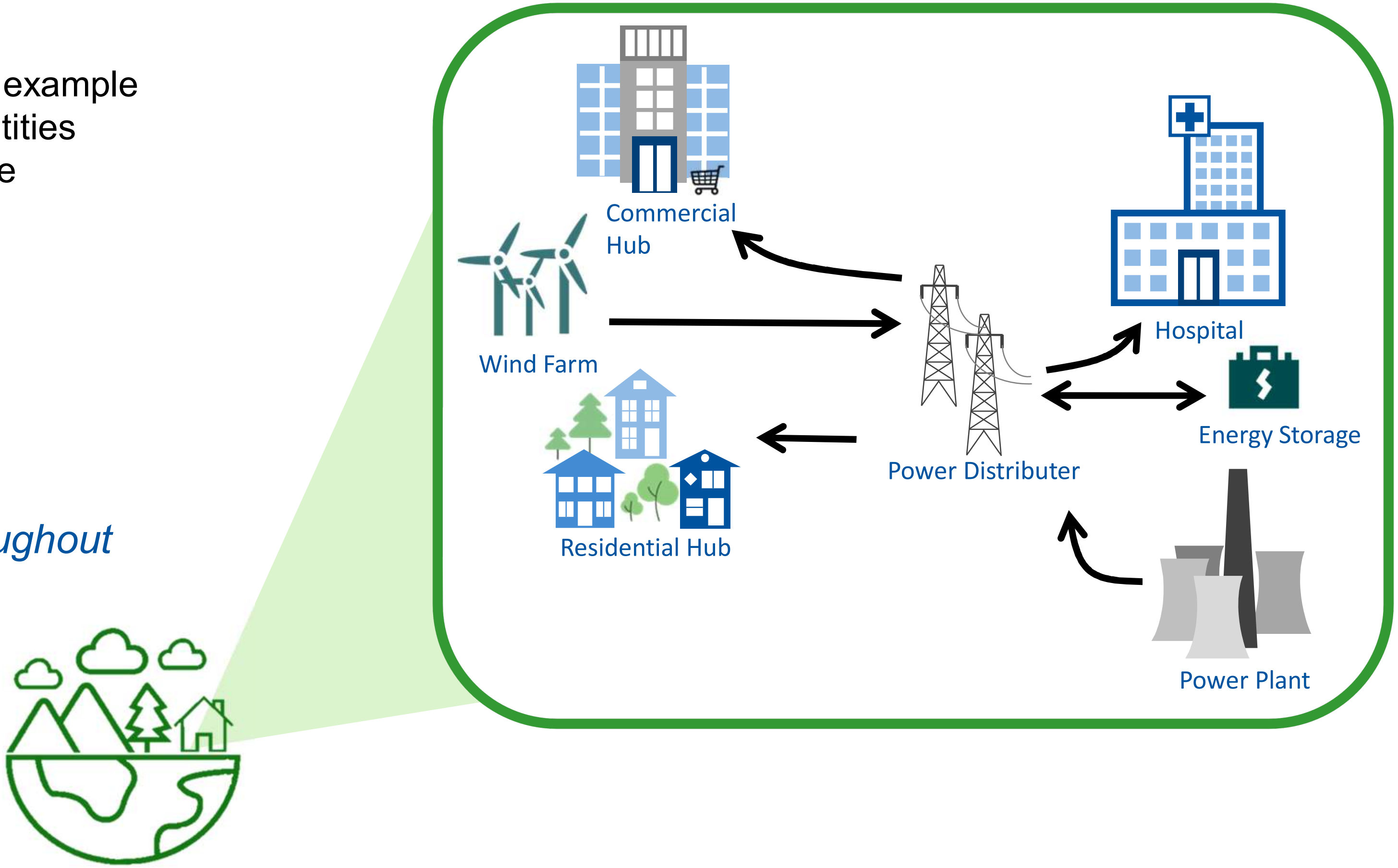
Digital Twins for Sustainable (Cyber-Physical) Systems?

Sustainable Evolvement of Systems

Planning *Citizen Energy Communities* example

- Citizens and small commercial entities
- Local energy generation & storage
- Local energy trading
- Citizens interact directly with electrical distribution system

Research Question:
How to enable system developers to iteratively evolve a system throughout its life cycle in a sustainable way?

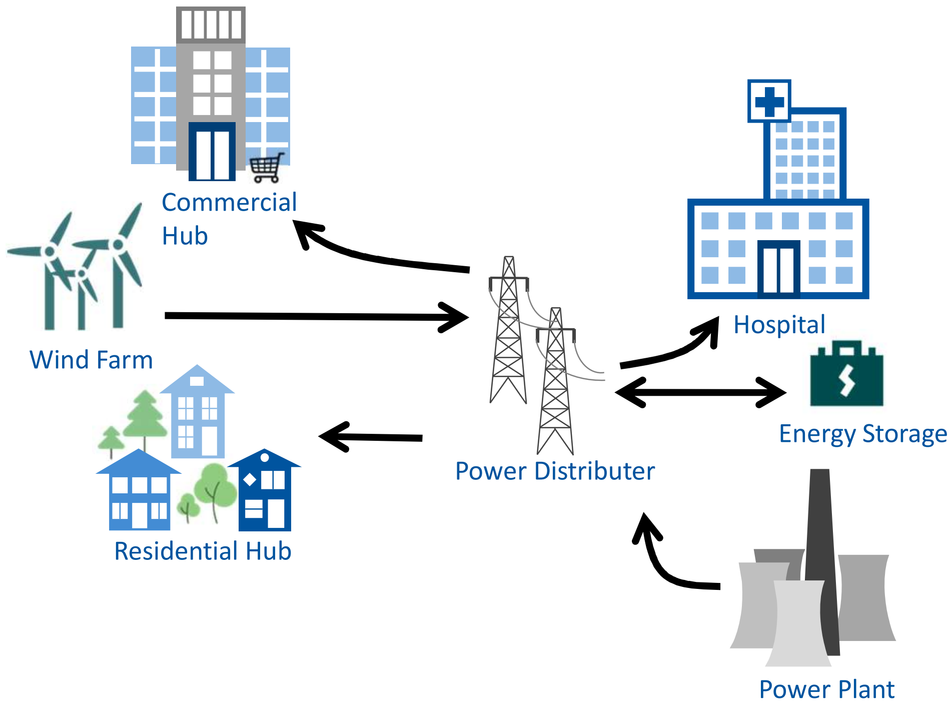


[GKM+23] G. Gramelsberger, H. Kausch, J. Michael, F. Piller, F. Ponci, A. Praktiknjo, B. Rumpe, R. Sota, S. Venghaus: Enabling Informed Sustainability Decisions: Sustainability Assessment in Iterative System Modeling. In: ME Workshop @MODELS, 2023.

Sustainable Evolvement of Systems

- Describe system with an architecture description language
  – MontiArc (MontiCore language workbench)

```
component CitizenEnergyCommunity{                MA
  … port …

  component Hospital hospital;
  component CommercialHub comHub;
  component ResidentialHub resHub;
  component WindFarm windfarm;
  component PowerDistributor distrib;
  component EnergyStorage storage;
  component CoalPowerplant powerplant;
}
```

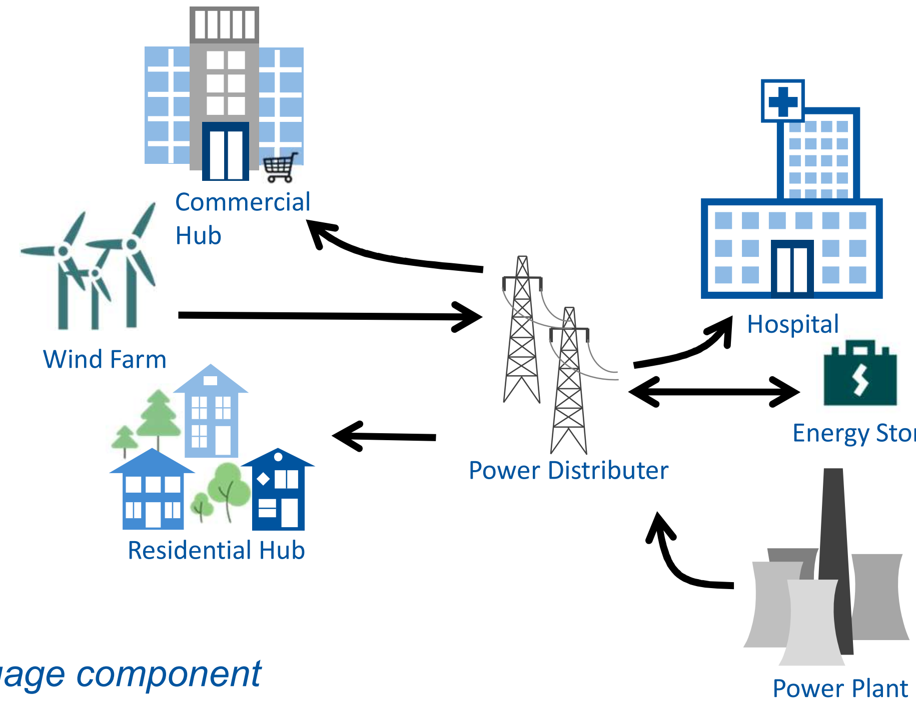


[GKM+23] G. Gramelsberger, H. Kausch, J. Michael, F. Piller, F. Ponci, A. Praktiknjo, B. Rumpe, R. Sota, S. Venghaus: Enabling Informed Sustainability Decisions: Sustainability Assessment in Iterative System Modeling. In: ME Workshop @MODELS, 2023.

Sustainable Evolvement of Systems

- Describe system with an architecture description language
  - MontiArc (MontiCore language workbench)

```
component CitizenEnergyCommunity{                MA
  … port …

  component Hospital hospital;
  component CommercialHub comHub;
  component ResidentialHub resHub;
  component WindFarm windfarm;
  component PowerDistributor distrib;
  component EnergyStorage storage;
  component CoalPowerplant powerplant;

  satisfy sustainability{
    sdg: [7,11,13]…
  }
}
```



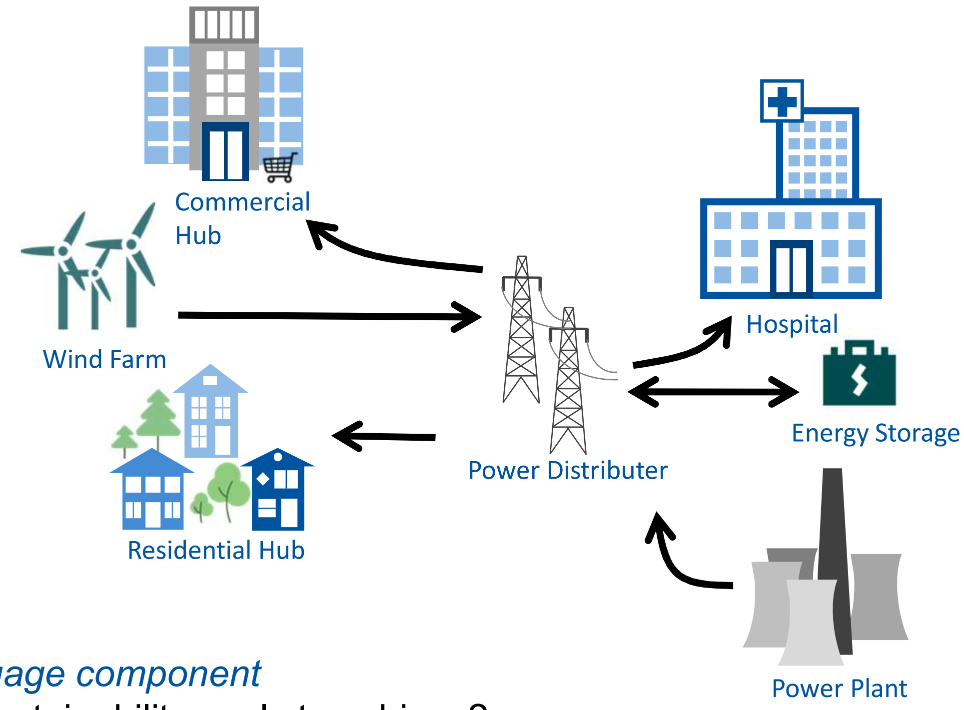
- *SDG language component*
  - Which sustainability goals to achieve?
  - DSL library: domain-specific indicators for energy planning

[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, 2023.

Sustainable Evolvement of Systems

- Describe system with an architecture description language
  - MontiArc (MontiCore language workbench)

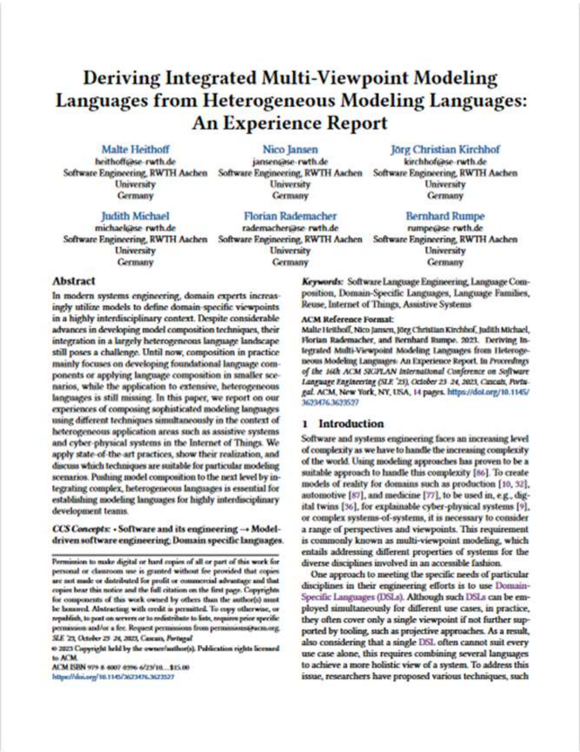
```
component CoalPowerplant{                          MA
  port
    out ElectricalEnergy ee;

  sustainability{
    type: energy, structure, process;
    indicators{
      consumption: coal;
      co2Emission: 950 gCO2/kWh;
      landscapeUsage: 1km^2;
      ...
    }
  }
}
```



- *SDG language component*
  - Which sustainability goals to achieve?
  - DSL library: domain-specific indicators for energy planning

[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, 2023.

Language Composition Mechanisms to Derive Language Families



Deriving Integrated Multi-Viewpoint Modeling Languages from Heterogeneous Modeling Languages: An Experience Report

Malte Heithoff, heithoff@se-rwth.de, Software Engineering, RWTH Aachen University, Germany
Nico Jansen, jansen@se-rwth.de, Software Engineering, RWTH Aachen University, Germany
Jörg Christian Kirchhof, kirchhof@se-rwth.de, Software Engineering, RWTH Aachen University, Germany
Judith Michael, michael@se-rwth.de, Software Engineering, RWTH Aachen University, Germany
Florian Rademacher, rademacher@se-rwth.de, Software Engineering, RWTH Aachen University, Germany
Bernhard Rumpe, rumpe@se-rwth.de, Software Engineering, RWTH Aachen University, Germany

Abstract

In modern systems engineering, domain experts increasingly utilize models to define domain-specific viewpoints in a highly interdisciplinary context. Despite considerable advances in developing model composition techniques, their integration in a largely heterogeneous language landscape still poses a challenge. Until now, composition in practice mainly focuses on developing foundational language components or applying language composition in smaller scenarios, while the application to extensive, heterogeneous languages is still missing. In this paper, we report on our experiences of composing sophisticated modeling languages using different techniques simultaneously in the context of heterogeneous application areas such as assistive systems and cyber-physical systems in the Internet of Things. We apply state-of-the-art practices, show their realization, and discuss which techniques are suitable for particular modeling scenarios. Pushing model composition to the next level by integrating complex, heterogeneous languages is essential for establishing modeling languages for highly interdisciplinary development teams.

CCS Concepts: **• Software and its engineering → Model-driven software engineering; Domain specific languages.**

ACM ISBN 979-8-4007-0396-6/23/10...$15.00
https://doi.org/10.1145/3623476.3623527

Keywords: Software Language Engineering, Language Composition, Domain-Specific Languages, Language Families, Reuse, Internet of Things, Assistive Systems

ACM Reference Format:
Malte Heithoff, Nico Jansen, Jörg Christian Kirchhof, Judith Michael, Florian Rademacher, and Bernhard Rumpe. 2023. Deriving Integrated Multi-Viewpoint Modeling Languages from Heterogeneous Modeling Languages: An Experience Report. In *Proceedings of the 16th ACM SIGPLAN International Conference on Software Language Engineering (SLE '23), October 23–24, 2023, Cascais, Portugal.* ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3623476.3623527

1 Introduction

Software and systems engineering faces an increasing level of complexity as we have to handle the increasing complexity of the world. Using modeling approaches has proven to be a suitable approach to handle this complexity [86]. To create models of reality for domains such as production [10, 32], automotive [87], and medicine [77], to be used in, e.g., digital twins [36], for explainable cyber-physical systems [9], or complex systems-of-systems, it is necessary to consider a range of perspectives and viewpoints. This requirement is commonly known as multi-viewpoint modeling, which entails addressing different properties of systems for the diverse disciplines involved in an accessible fashion.

One approach to meeting the specific needs of particular disciplines in their engineering efforts is to use Domain-Specific Languages (DSLs). Although such DSLs can be employed simultaneously for different use cases, in practice, they often cover only a single viewpoint if not further supported by tooling, such as projective approaches. As a result, also considering that a single DSL often cannot suit every use case alone, this requires combining several languages to achieve a more holistic view of a system. To address this issue, researchers have proposed various techniques, such

*Capturing **complex systems** requires **different techniques** for composing DSLs, e.g., for sustainability*

*For the composition of **language families, embedding** and **aggregation** are needed*

…more details in the paper

International Conference on Software Language Engineering

To the **Paper**
se-rwth.de/publications

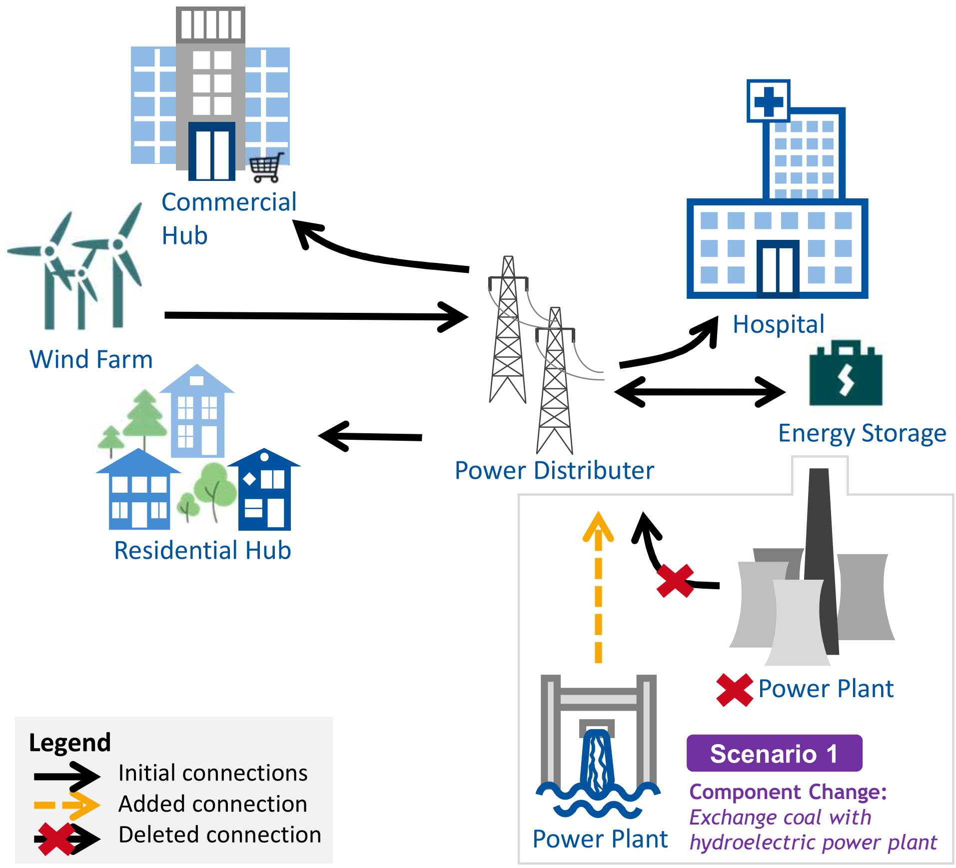
[HJK+23] M. Heithoff, N. Jansen, J. C. Kirchhof, J. Michael, F. Rademacher, B. Rumpe: Deriving Integrated Multi-Viewpoint Modeling Languages from Heterogeneous Modeling Languages: An Experience Report. SLE Conference 2023

Sustainable Evolvement of Systems

- Evolution Scenario 1 | Component Change
  - Black-box architecture is unchanged

MA

```
component HydroPowerplant{
  port
    out ElectricalEnergy ee;

  sustainability{
    type: energy, structure, process;
    indicators{
      consumption: renewable, hydro;
      co2Emission: 24 gCO2/kWh;
      landscapeUsage: 2km^2;
      ...
    }
  }
}
```

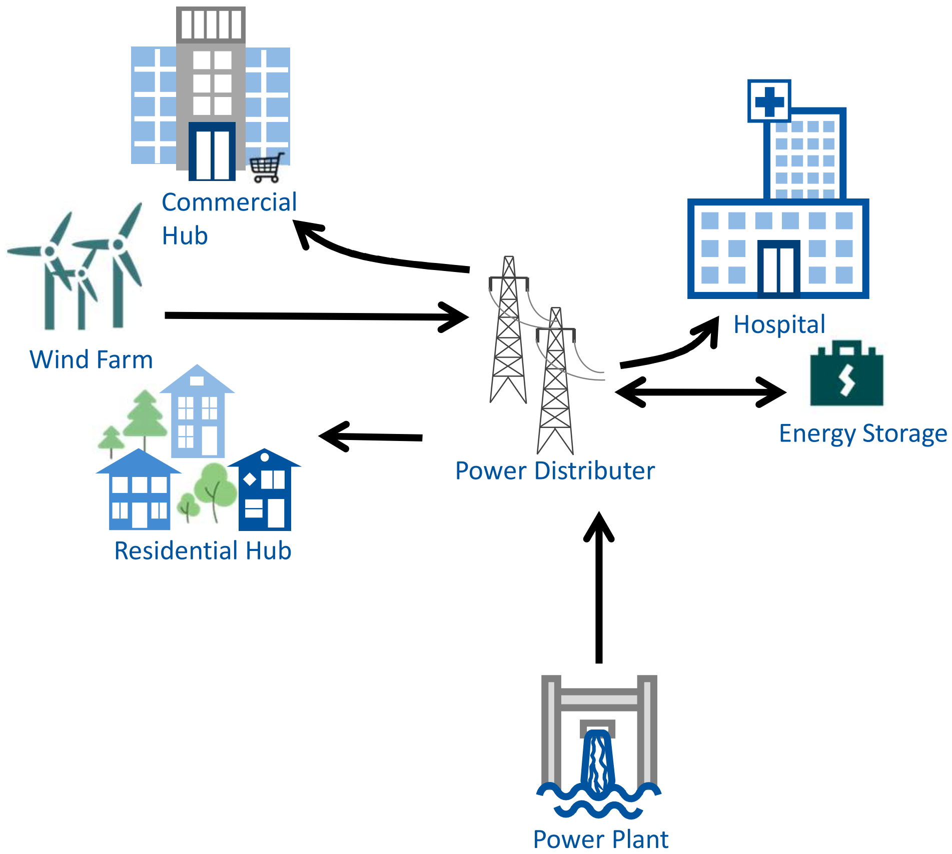


[GKM+23] G. Gramelsberger, H. Kausch, J. Michael, F. Piller, F. Ponci, A. Praktiknjo, B. Rumpe, R. Sota, S. Venghaus: Enabling Informed Sustainability Decisions: Sustainability Assessment in Iterative System Modeling. In: ME Workshop @MODELS, 2023.

Evolution Scenario 1 | Component Change

- *Assessment Result*
  - Reduced the power plant's CO_2 emissions by over 95%
  - More landscape usage
  - Slightly positive effects for SDGs 7, 11, and 13

- *Sustainability Assessment*
  - assessed by experts or
  - passed on to assessment systems
    - domain-specific systems
    - *Sustainability Evaluation Experience* R (SEER) [KMC+20]



[KMC+20] J. Kienzle, G. Mussbacher, B. Combemale, L. Bastin, N. Bencomo, J.-M. Bruel, C. Becker, S. Betz, R. Chitchyan, B.H.C. Cheng, S. Klingert, R.F. Paige, B. Penzenstadler, N. Seyff, E. Syriani, C.C. Venters: Toward model-driven sustainability evaluation. Commun. ACM 63, 3, 2020.

Sustainable Evolvement of Systems

International Workshop on
Models and Evolution
Special theme: Sustainability

Enabling Informed Sustainability Decisions: Sustainability Assessment in Iterative System Modeling

Gabriele Gramelsberger, *Theory of Science and Technology*, *RWTH Aachen University*, gramelsberger@humtec.rwth-aachen.de
Hendrik Kausch, *Software Engineering*, *RWTH Aachen University*, kausch@se-rwth.de
Judith Michael *, *Software Engineering*, *RWTH Aachen University*, michael@se-rwth.de
Frank Piller, *Technology and Innovation Management*, *RWTH Aachen University*, piller@time.rwth-aachen.de
Ferdinanda Ponci, *E.ON Research Center at RWTH Aachen University*, fponci@eonerc.rwth-aachen.de
Aaron Praktiknjo, *E.ON Research Center at RWTH Aachen University*, apraktiknjo@eonerc.rwth-aachen.de
Bernhard Rumpe, *Software Engineering*, *RWTH Aachen University*, rumpe@se-rwth.de
Rega Sota, *School of Business and Economics*, *RWTH Aachen University*, rega.sota@soecon.rwth-aachen.de
Sandra Venghaus, *School of Business and Economics*, *RWTH Aachen University*, venghaus@soecon.rwth-aachen.de

***Abstract*—When planning, creating, and evolving systems throughout their lifecycle, it is essential to assess their impact on our world. Despite this pressing need, existing structured methods for systematically assessing social, economic, and environmental impacts are not related to targets of the United Nations' sustainable development goals. Moreover, existing Architecture Description Languages (ADLs) lack concepts and tooling for sustainability assessment. Our aim is to allow modeling systems, their sustainability properties, and sustainability questions in a structured manner for a wide domain. This paper proposes the engineering and design of a domain-specific language for sustainability assessment embedded into ADLs and showcases its use for evaluating a citizen energy community system as a case study. We discuss possibilities on how to use such models in their further processing and explore challenges in technical realization. This initial step towards standardizing the sustainability assessments of modeled systems throughout the development is both comprehensive and formal so that developers can make informed, sustainable decisions based on consequence assessments upfront.**

***Index Terms*—Systems Engineering, Domain-Specific Languages, Model-Driven Engineering, Sustainable Development Goals, Life-Cycle Sustainability Assessment, Architecture Description Language, Energy Planning**

I. INTRODUCTION

Motivation. When developing and evolving systems, technologies, and processes over a longer period of time sustainability plays a significant role in each decision point of developers. Such systems include the production domain, Internet of Things (IoT), Cyber-Physical System (CPS), or pure software systems. Development decisions may lead to negative influences on different sustainability goals [1] in the areas of social, economic, and environmental sustainability [2].

Research Question. We tackle the main research question of how to enable system developers to iteratively evolve a system throughout its life cycle in a sustainable way.

Contribution. To make these informed decisions, we suggest a model-based approach that incorporates sustainability descriptions in Architecture Description Language (ADL) models. This paper explores and introduces an approach to combine sustainability assessment defined in a Domain-Specific Language (DSL) with ADL models throughout an iterative development process. The approach supports decision-making through a system's evolution and leads to the implementation of sustainable systems. As a running example, we show two development scenarios in an energy planning case study for a citizen energy community.

Structure. We provide foundations, use a running example to introduce the methodology for sustainable system development, and conclude with a roadmap for implementing DSLs and assessing sustainability.

II. PRELIMENARIES

Architecture Description Languages. For modeling systems, ADLs [3] offer great possibilities for iterative development. Most ADLs follow the component-connector approach, where a system architecture is defined by its components/parts and their connectors/ports. Often, additional (behavior) description possibilities are offered for atomic components through language compositions, e.g., state charts [4]. Components define their communication interface through input and output ports.

*Corresponding author.

Facilitate the *sustainability decision-making*
throughout the *lifecycle of systems*
by embedding *sustainability descriptions* in *ADL models*

…more in the paper!

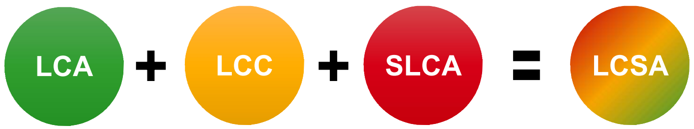
To the
Preprint
se-rwth.de/publications

[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, 2023.

E.ON Energy Research Center · humtec · Research Area Technology, Innovation, Marketing, Entrepreneurship · Juniorprofessur für Decision Analysis and Socio-economic Assessment · Software Engineering · RWTH AACHEN UNIVERSITY

Sustainability Assessment

- *Lifecycle Sustainability Assessment* (LCSA)
  - LCA = Environmental Life Cycle Assessment
  - LCC = LCA-type Life Cycle Costing
  - SLCA = Social Life Cycle Assessment



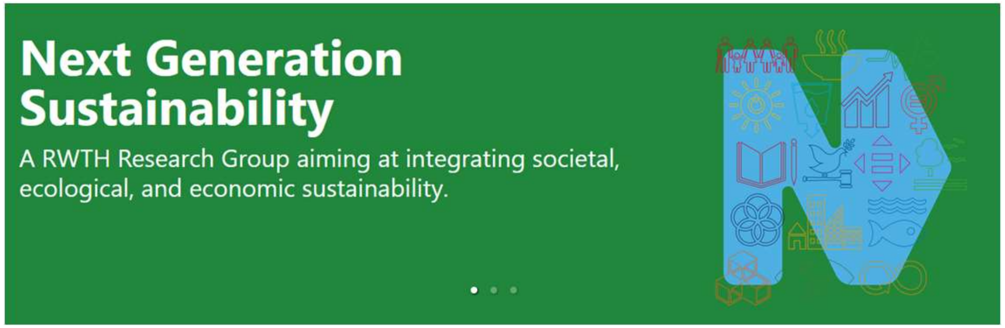
- Lack a *connection* between *LCSA indicators* and *SDG goals* and more concrete target
  - As of 2022, 14 SDG goals have not yet been assigned LCSA indicators

- *(Some) Challenges*
  - Tool supported but also *manual effort*
  - Data *availability*
  - Some approaches in practice consider *only two* of the *three main sustainability aspects*
  - Lack *interconnectedness* among the three areas
  - Do not follow *cause-effect chains*
  - System *boundaries* unclear/ inconsistent
  - Non-transparent *weighting of results*
  - *Lack of agreement* in the international community on *social targets* to achieve for many social indicators
  - …

Sources:
- *M. Finkbeiner, E.M. Schau, A. Lehmann, M. Traverso: Towards Life Cycle Sustainability Assessment. Sustainability, 2010.*
- *S. Valdivia, J. G. Backes, M. Traverso, G. Sonnemann, S. Cucurachi, J. B. Guinée, T. Schaubroeck, M. Finkbeiner, N. Leroy-Parmentier, C. Ugaya, C. Peña, A. Zamagni, A. Inaba, M. Amaral, M. Berger, J. Dvarioniene, T. Vakhitova, C. Benoit-Norris, M. Prox, R. Foolmaun, M. Goedkoop: Principles for the application of life cycle sustainability assessment," The International Journal of Life Cycle Assessment, vol. 26, no. 9, 2021.*
- *J. Martínez-Blanco, A. Lehmann, P. Muñoz, A. Antón, M. Traverso, J. Rieradevall, M. Finkbeiner: Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. Journal of Cleaner Production, vol 69, 2014.*

Next Generation Sustainability

- *Interdisciplinary* research group from *RWTH Aachen*
  - *Mechanical Engineering:* Manufacturing Technology, Advanced Mining Tech., Anthropogenic Material Cycles, Textile Tech., Industrial Eng. and Ergonomics
  - *Energy Engineering:* Aut. of Complex Power Syst., Energy Syst. Economics, Sustainability in Civil Eng., Tech. Thermodynamics
  - *Informatics:* Software Engineering, Databases, Computer Graphics & Multimedia, HPC, Comm. and Distributed Syst.
  - *Chemistry, Geographics:* Bioinorganic Chemistry, Geography, Comp. Geoscience, Geothermics and Reservoir Geophysics
  - *Business Administration:* Applied Economics, Planning Theory, Controlling, Technology & Innovation Management
  - *Social Science:* Human Tech. Center, Philosophy of Science and Tech., Decision Analysis and Socio-economic Assessment, Computational Social Science
- Developing a holistic approach for *sustainability assessment* aiming to cover all UN SDGs



- Sustainability assessment of *technologies*, *products*, and *policies*
  - Different *levels of analysis,* e.g., global, national, regional, industry, product-level
- Participatory *open science* approach
  - open-up the development for stakeholders worldwide

https://nextgen.rwth-aachen.de

HOW CAN OUR RESEARCH CONTRIBUTE TO THE SUSTAINABLE **ENGINEERING** OF DIGITAL TWINS?

Software Engineering and Sustainability

Sustainable Business Practices

How Green Is Your Software?

by Sanjay Podder, Adam Burden, Shalabh Kumar Singh, and Regina Maruca

September 18, 2020

Illustration by Ricardo Tomás

Harvard Business Review: https://hbr.org/2020/09/how-green-is-your-software

Green Software Foundation | About | Working Groups | Projects | Resources | Articles

10 RECOMMENDATIONS FOR GREEN SOFTWARE DEVELOPMENT

Green Software Foundation: https://greensoftware.foundation/articles/10-recommendations-for-green-software-development

Forbes

FORBES > INNOVATION

The Power Of Sustainable Software

Alexander Belokrylov Forbes Councils Member
Forbes Technology Council COUNCIL POST | Membership (Fee-Based)

Forbes: https://www.forbes.com/sites/forbestechcouncil/2022/08/18/the-power-of-sustainable-software/

GREEN

Energy, Hardware, Software, Software Engineering Processes, …

GREEN (washing?)

Energy, Hardware, Software,
Software Engineering Processes, …

Green IT

- ecological sustainability
- aims to reduce the environmental impacts associated with conventional IT, e.g.,
  - energy efficient hardware, data centers, server virtualization, monitoring systems

13 CLIMATE ACTION

The biggest impact of ICT as an industry is the amount of *greenhouse gas emissions*.

Source: https://www.innoq.com/en/articles/2023/02/what-is-sustainable-software/

1.5% to 4% of global GHG emissions

Bieser, J. C. T., Hintemann, R., Hilty, L. M., & Beucker, S. (2023). A review of assessments of the greenhouse gas footprint and abatement potential of information and communication technology. Environmental Impact Assessment Review, 99.

Green software development

Green Software Foundation

- Focus on & control features with *higher power consumption* and *common usage scenarios*
- Reduce *data usage*
- Limit *computational accuracy*
- *Monitor* real-time energy consumption of the application
- Developing and using *less-power-consuming ML models*
- Monitor *real-time power consumption* during development

Source: https://greensoftware.foundation/articles/10-recommendations-for-green-software-development

Sustainable Software Engineering

Six principles for Sustainable Software Engineers

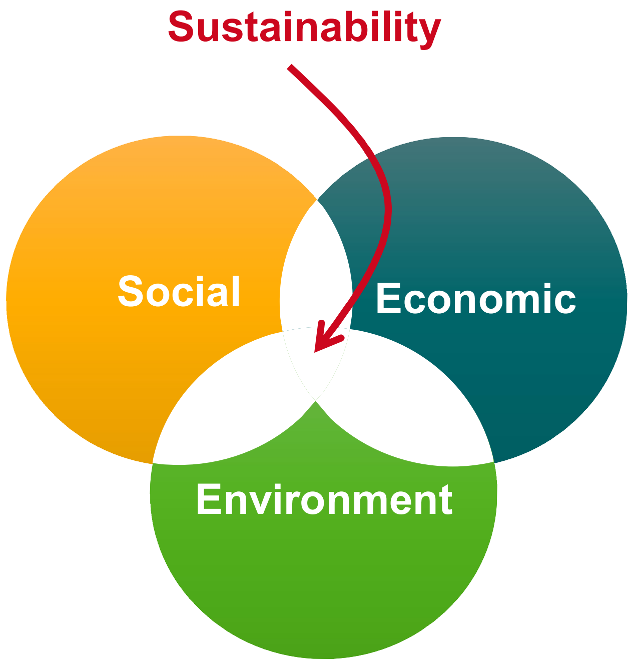
- *Carbon, Electricity, and Hardware Efficiency* when building applications
- *Carbon Awareness*: Consume electricity with the lowest carbon intensity
- *Measurement* to improve sustainability
- *Climate Commitments*: Defining the exact mechanism of carbon reduction

Source: https://learn.microsoft.com/en-us/training/modules/sustainable-software-engineering-overview/

Human Sustainability in SE

- Impact sourcing
- Ethical outsourcing
- Fair trade software

Ramautar, V., Overbeek, S., España, S. (2021). Human Sustainability in Software Development. In: Calero, C., Moraga, M.Á., Piattini, M. (eds) Software Sustainability. Springer

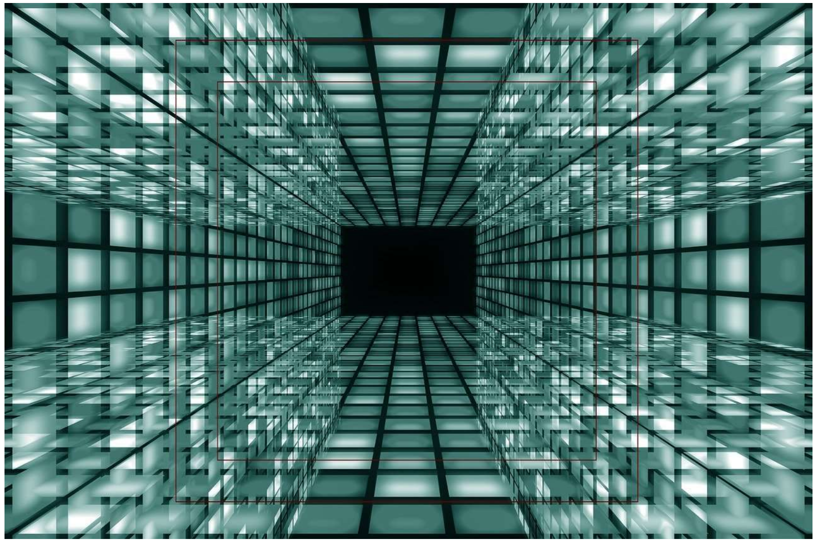


Sustainable Software Engineering

Sustainability is *"preserving the function of a system over a defined time span"*

– 3 variables: system, function, and time

B. Penzenstadler, "Towards a definition of sustainability in and for software engineering," In ACM Symp. on Applied Comp. (SAC), 2013.



Perspectives

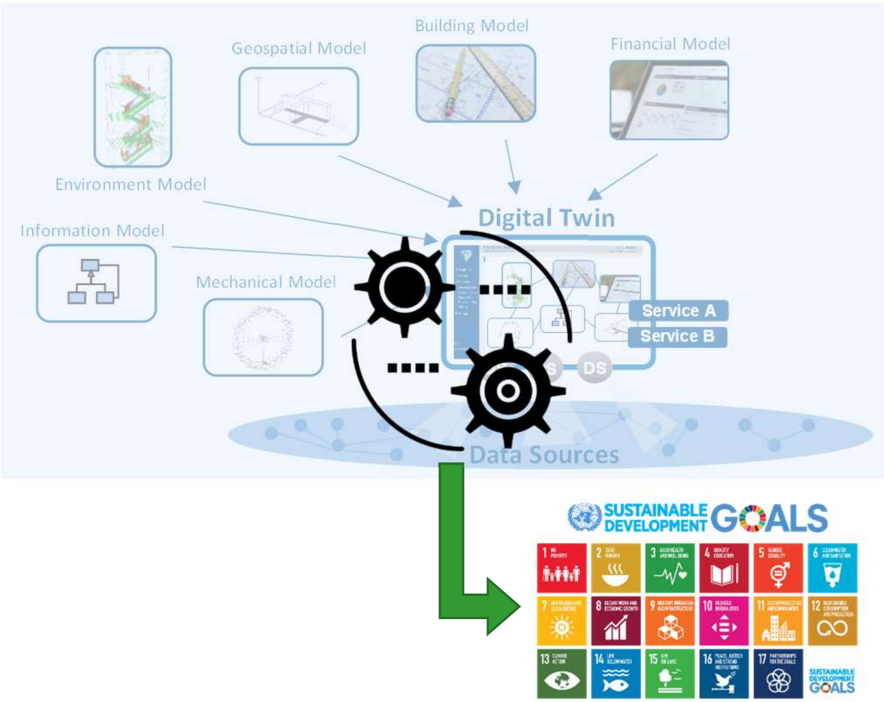
– *Development processes*
  - SE processes with responsible use of ecological, human, financial resources

– *Software maintenance*
  - maintain and evolve software with min. environmental impact, well-managed knowledge, sufficient economic balance

– *System production*
  - software is a concrete product including its hardware and the resources needed for production

– *System usage*
  - entire period of use of the software and its operational environment

Sustainable Digital Twin Engineering



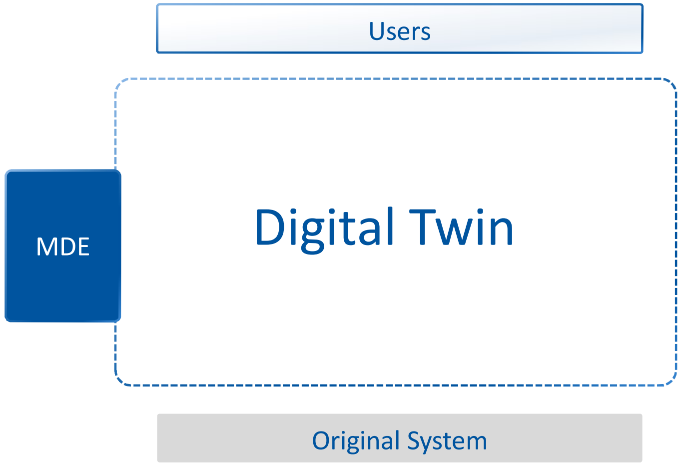
Digital twins are ***active software systems***

- Digital twins can be sustainably developed
  - Apply practices used for other software systems

Investigate

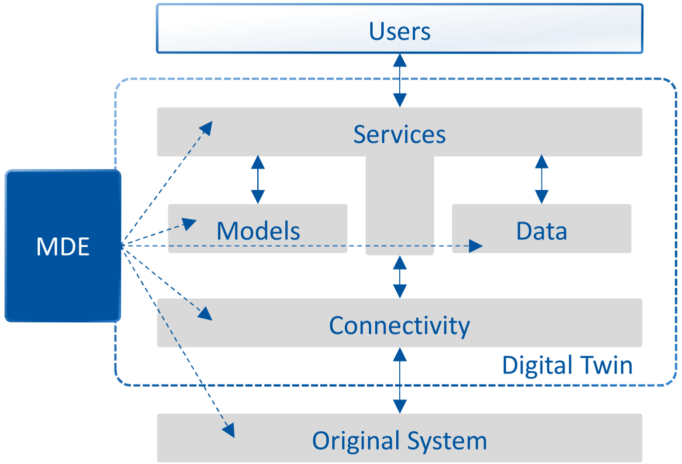
- What are *specifics* for digital twins?
- How can *MDE* support us in sustainable DT engineering?
- What are *challenges* using MDE for sustainable DT engineering?

Model-Driven Engineering of Digital Twins | Benefits



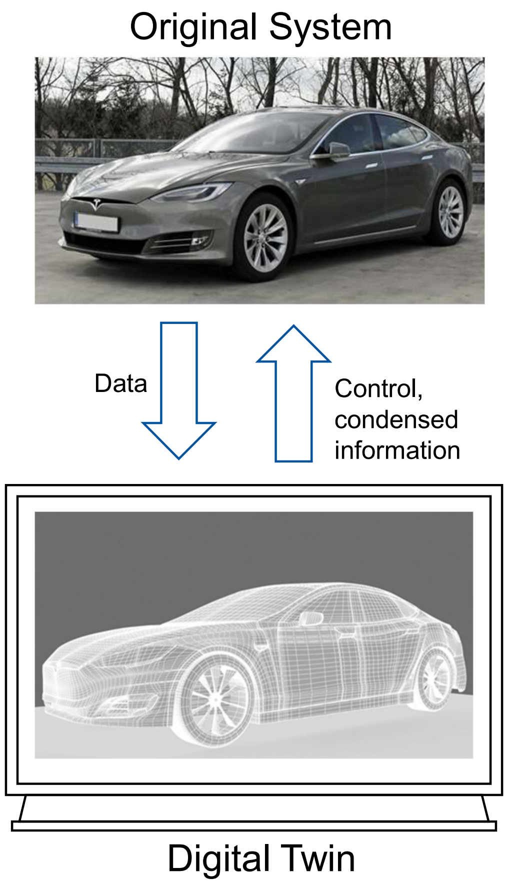
- Increased development speed and reduced development time
- Better software quality, e.g., less bugs,
  - well-defined domain-specific modeling languages, automated model checking, transformation, test and test case generation,…
- Improved maintainability
  - Cross-cutting implementation aspects can be changed in one place which again reduces development time
- Empowered domain experts by providing low-code platforms for the development of digital twins
- …

MDE of Digital Twins | Where and how to consider sustainability?



- Models
  - in addition to models for DT engineering
  - *model sustainability*, e.g., sustainability requirements and goals for DT engineering process and runtime of the DT
- Data
  - Measure sustainability *targets & KPIs*
  - Reduce data usage
- Services
  - *Monitor* relevant indicators
  - *Simulate, forecast* sustainability indicators
  - Relate *low-level* sustainability goal with *higher-level* SDGs
  - *Analyze the DT* and the "twinned" system and suggest more sustainable processes, connectivity, hardware, less power consuming services,…
  - *Visualize* metrics, analysis results

MDE of Digital Twins | Costs & Research topics



- *Understand the costs of automation*
  - balance high quality in engineering processes vs. not wasting resources
  - analyze processes e.g., nightly built, run tests, deploy daily
    - reduce energy consumption by, e.g., iterative builds
- *Power consuming services & models* within DTs
  - analyze services and, e.g., use less-power-consuming ML models, re-use pre-trained ML models to avoid costly retraining of networks
- *Analyze the „twinning“ functionality*
  - Which degree of synchronization is needed?
  - What accuracy of models is needed?
- *Composition/ Federation* of DTs
  - How to compose DTs to improve maintainability?
  - What are the costs of federation vs. integration?

Finding balances is not easy!

Model-Based DevOps project

Automate the DevOps cycle by leveraging digital twins and model-based development

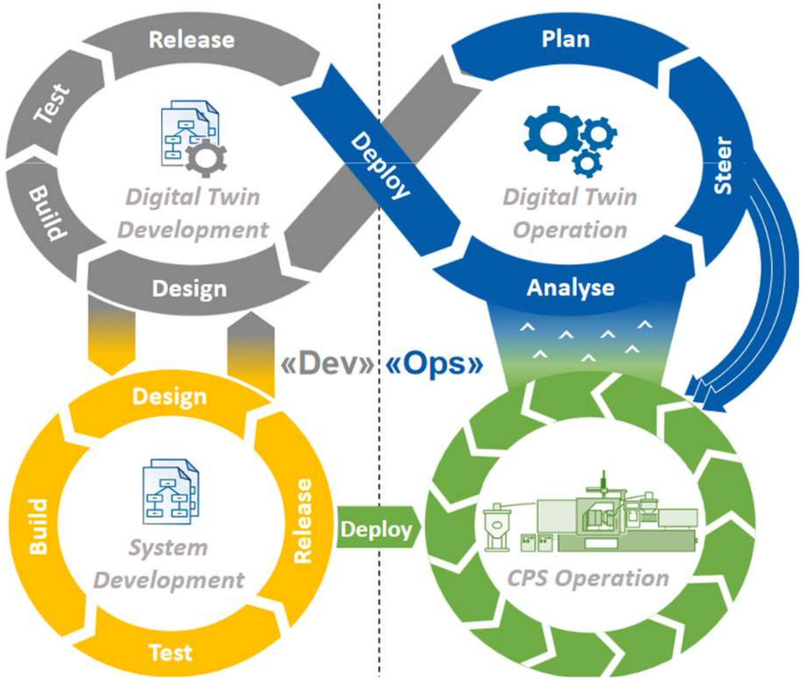
with Université de Rennes & Universität Stuttgart

Application Domain: *Sustainable Production*

Research Goals

- *Composability* of Digital Twins
- Definition of a *Reference Model* of Digital Twins and Data Models
- Improving the *Modeling of Ops and Dev Activities*
- Establishing the *Dev-to-Ops-to-Dev Modeling Continuum*
- Automatically *Synthesizing* Dev-to-Ops-to-Dev Models

More: https://mbdo.github.io/



[CJP+23] B. Combemale, J. Jézéquel, Q. Perez, D. Vojtisek, N. Jansen, J. Michael, F. Rademacher, B. Rumpe, A. Wortmann, J. Zhang: *Model-Based DevOps: Foundations and Challenges*. In: ModDiT Workshop at MODELS 2023

"What you do makes a difference, and you have to decide what kind of difference you want to make."

Jane Goodall

LET'S MAKE A DIFFERENCE!

- Use DTs to *assess* the sustainability of systems
- Develop *sustainable engineering methods* to create DTs
- Develop *sustainable methods* to run DTs
- *Model* sustainability

Feel free to contact me:

michael@se-rwth.de

@judithmichael.bsky.social

@JudithMichael@mastodon.acm.org

*@JudithMichael_*

SE Software Engineering | RWTH AACHEN UNIVERSITY

Selected References

Digital Twins

- [HJM+24] M. Heithoff, N. Jansen, J. Michael, F. Rademacher, B. Rumpe: *Model-Based Engineering of Multi-Purpose Digital Twins in Manufacturing*. In: Digital Twin - Fundamentals and Applications, Springer, 2024.
- [MSW23] J. Michael, M. Schwammberger, A. Wortmann: *Explaining Cyber-Physical System Behavior with Digital Twins*. In: IEEE Software. 2023
- [CJP+23] B. Combemale, J. Jézéquel, Q. Perez, D. Vojtisek, N. Jansen, J. Michael, F. Rademacher, B. Rumpe, A. Wortmann, J. Zhang: *Model-Based DevOps: Foundations and Challenges*. In: ModDiT Workshop at MODELS 2023
- [HKM+23] M. Heithoff, M. Konersmann, J. Michael, B. Rumpe, F. Steinfurth: *Challenges of Integrating Model-Based Digital Twins for Vehicle Diagnosis*. In: ModDiT WS at MODELS 2023
- [HHMR23] M. Heithoff, A. Hellwig, J. Michael, B. Rumpe: *Digital Twins for Sustainable Software Systems.* In: GREENS 2023
- [FHM+23] S. Fur, M. Heithoff, J. Michael, L. Netz, J. Pfeiffer, B. Rumpe, A. Wortmann: *Sustainable Digital Twin Engineering for the Internet of Production.* In: Digital Twin Driven Intelligent Systems and Emerging Metaverse, 2023.
- [MNN+22] J. Michael, I. Nachmann, L. Netz, B. Rumpe, S. Stüber: *Generating Digital Twin Cockpits for Parameter Management in the Engineering of Wind Turbines*. Modellierung'22
- [BMR+22] D. Bano, J. Michael, B. Rumpe, S. Varga, M. Weske: *Process-Aware Digital Twin Cockpit Synthesis from Event Logs*. Journal of Computer Languages (COLA) 70, 2022.
- [DHM+22] M. Dalibor, M. Heithoff, J. Michael, L. Netz, J. Pfeiffer, B. Rumpe, S. Varga, A. Wortmann: *Generating Customized Low-Code Development Platforms for Digital Twins*. Journal of Computer Languages (COLA) 70, 2022.
- [MPRW22] J. Michael, J. Pfeiffer, B. Rumpe, A. Wortmann: *Integration Challenges for Digital Twin Systems-of-Systems*. SESoS'22
- [BHK21] T. Brockhoff, M. Heithoff, I. Koren, J. Michael, J. Pfeiffer, B. Rumpe, M.S. Uysal, W. M. P. van der Aalst, A. Wortmann: *Process Prediction with Digital Twins*. Models@runtime'21
- [DMR+20] M. Dalibor, J. Michael, B. Rumpe, S. Varga, A. Wortmann: *Towards a Model-Driven Architecture for Interactive Digital Twin Cockpits*. ER'20.
- [KMR+20] J. C. Kirchhof, J. Michael, B. Rumpe, S. Varga, A. Wortmann: *Model-driven Digital Twin Construction: Synthesizing the Integration of Cyber-Physical Systems with Their Information Systems*. MODELS'20.

Modeling in Industry 4.0

- [BDJ+22] P. Brauner, M. Dalibor, M. Jarke, I. Kunze, I. Koren, G. Lakemeyer, M. Liebenberg, J. Michael, J. Pennekamp, C. Quix, B. Rumpe, W. van der Aalst, K. Wehrle, A. Wortmann, M. Ziefle: *A Computer Science Perspective on Digital Transformation in Production*. ACM TIOT 3, 2022
- [FMR+22] K. Feichtinger, K. Meixner, F. Rinker, I. Koren, H. Eichelberger, T. Heinemann, J. Holtmann, M. Konersmann, J. Michael, E.- M. Neumann, J. Pfeiffer, R. Rabiser, M. Riebisch, K. Schmid: *Industry Voices on Software Engineering Challenges in Cyber-Physical Production Systems Engineering*. In: ETFA'22, IEEE, 2022.

Digital Shadows

- [MKD+23] J. Michael, I. Koren, I. Dimitriadis, J. Fulterer, A. Gannouni, M. Heithoff, A. Hermann, K. Hornberg, M. Kröger, P. Sapel, N. Schäfer, J. Theissen-Lipp, S. Decker, C. Hopmann, M. Jarke, B. Rumpe, R. Schmitt, G. Schuh: *A Digital Shadow Reference Model for Worldwide Production Labs.* In: Internet of Production: Fundamentals, Applications and Proceedings, 2023.
- [BBD+21] F. Becker, P. Bibow, M. Dalibor, A. Gannouni, V. Hahn, C. Hopmann, M. Jarke, I. Koren, M. Kröger, J. Lipp, J. Maibaum, J. Michael, B. Rumpe, P. Sapel, N. Schäfer, G. J. Schmitz, G. Schuh, and A. Wortmann: *A conceptual model for digital shadows in industry and its application*. ER'21

Current
Publications
se-rwth.de/publications