Unlocking Potential: Rocking the Sustainable Future with Digital Twins

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Real world challenges (some…)

- Water scarcity affects more than 40% of the world’s population.
- More than 700 million people still live in extreme poverty.
- 9 out of 10 urban residents breathe polluted air.
- Global emissions of CO$_2$ have increased by almost 50% since 1990.
- One fifth of young people are not in education, employment or training.
- 617 million children and adolescents lack min. proficiency in reading and mathematics.

Should we really continue on this „highway to hell“?
How can we from ModDiT 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

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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
“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.”
Digital Twins of Cyber-Physical Systems
Digital Twins of Systems
Digital Twins as complex, long-lasting, software-intensive systems

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.

contextual data and their aggregation and abstraction
Digital Twins enable us to connect reality with the digital world and back
HOW CAN OUR RESEARCH CONTRIBUTE TO THE SUSTAINABLE ENGINEERING OF DIGITAL TWINS?
Software Engineering and Sustainability

How Green Is Your Software?
by Sanjay Poddar, Adam Burden, Shalabh Kumar Singh, and Regina Maruca

September 18, 2020


10 RECOMMENDATIONS FOR GREEN SOFTWARE DEVELOPMENT

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

The Power Of Sustainable Software

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

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


<table>
<thead>
<tr>
<th>Green software development</th>
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<tbody>
<tr>
<td>- Focus on &amp; control features with higher power consumption and common usage scenarios</td>
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<tr>
<td>- Reduce data usage</td>
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<tr>
<td>- Limit computational accuracy</td>
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<tr>
<td>- Monitor real-time energy consumption of the application</td>
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<tr>
<td>- Developing and using less-power-consuming ML models</td>
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<tr>
<td>- Monitor real-time power consumption during development</td>
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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

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
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!
HOW CAN WE USE DTs TO ASSESS THE SUSTAINABILITY OF COMPLEX, SOFTWARE-INTENSIVE SYSTEMS?
Digital Twins for Sustainability

• Creating 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

• Digital Twin services to
  – enable simulation of different variants of digital twins before building the physical one to improve resource efficiency
  – facilitate optimizing production processes towards waste reduction and energy saving allowing a responsible production
  – 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
  - ...

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DT during *implementation/generation* of a software system

**Life cycle of the actual object:** Software

- **Design**
- **Impl./Generation**
- **Operation**
- **End-of-Life**

**Digital Twin of individual software, or a Software Product Line**

- **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
  - …
DT during operation of a software system

Life cycle of the actual object: **Software**

- **Design**
- **Impl./Generation**
- **Operation**
- **End-of-Life**

**DTs of SPL software**

**Digital Twin of individual software, or a Software Product Line**

- 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

- …

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

**Life cycle of the actual object:** *Software*

- **Design**
- **Impl./Generation**
- **Operation**
- **End-of-Life**

*Digital Twins of SPL software*

*Digital Twin of individual software, or a Software Product Line*

- 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
- …

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

- ...more in the paper

- Questions to discuss
  - Is the engineering of an additional software system (the DT) sustainable?
  - What are pros and cons for including sustainability services directly in software systems?
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?

Sustainable Evolvement of Systems

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

```java
component CitizenEnergyCommunity{
  ... port ...
  component Hospital hospital;
  component CommercialHub comHub;
  component ResidentialHub resHub;
  component WindFarm windfarm;
  component PowerDistributor distrib;
  component EnergyStorage storage;
  component CoalPowerplant powerplant;
}
```

Sustainable Evolvement of Systems

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

```plaintext
component CitizenEnergyCommunity{
  ... 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

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### Sustainability Assessment

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

- (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

LCSA

- **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

Sources:
Conceptual model-based framework
“Sustainability Evaluation Experience R” (SEER)

Sustainable Evolvement of Systems

- Indicators in components
  - Iterative Development | Component Change

```java
component HydroPowerplant{
  port
    out ElectricalEnergy ee;

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

Legend
- Initial connections
- Added connection
- Deleted connection

Scenario 1
Component Change: Exchange coal with hydroelectric power plant

References:
Facilitate the sustainability decision-making throughout the lifecycle of systems by embedding sustainability descriptions in ADL models...more on Tuesday!
**Scientific Commercial Break**

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**Digital Twin Evolution**

**Special Theme**

Digital twins are increasingly being leveraged within research and industrial contexts to leverage and aggregate physical system data across a multitude of applications. This special theme explores the advancements in the digital twin paradigm, focusing on the evolution of digital twin capabilities, their integration into various industries, and the challenges and opportunities they present. The theme emphasizes the importance of developing robust, interoperable, and scalable digital twin solutions that can effectively model, simulate, and optimize complex physical systems.

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**Call for Papers**

**Software and Systems Modeling**

**Theme Section:** Modeling and Sustainability

This perception of the value and quality of modern engineered systems is changing. In addition to their functional and non-functional properties, modern systems are also evaluated by their sustainability attributes. The next generation of systems will be characterized by a broadened notion of sustainability—encompassing their entire life cycle driven by efficient value creation mechanisms. Current systems engineering practices fall short to support these ambitions due to the lack of multi-criteria and multi-tiered nature of sustainability, and need for a novel approach.

The purpose of this special section is to understand and convey the sustainability properties of engineered systems. Modelling languages and tools support subject matter experts in exploring their design, process models allow for assessing effect of trade-offs across the entire system engineering process, and case studies allow for the monitoring and examination of sustainability properties of engineered systems. Models and tools support in exploring the sustainability properties of engineered systems. Modelling languages and tools support subject matter experts in exploring their design, process models allow for assessing effect of trade-offs across the entire system engineering process, and case studies allow for the monitoring and examination of sustainability properties of engineered systems. Models and tools support in exploring the sustainability properties of engineered systems.

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**Important Dates**

- **Submit Proposal:** 01 Dec 2023
- **Paper Submission:** 05 Mar 2024
- **Notifications:** 01 May 2024

**References**

- [Digital Twin Evolution](#)
- [Digital Twin Conference](#)
- [Digital Twin Applications](#)
- [Digital Twin in Manufacturing](#)
- [Digital Twin in Health Care](#)

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**SE Software Engineering | RWTH Aachen**

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To this end, the *Journal of Software and Systems Modeling* (JSSM) proposes theme sections on “Modeling and Sustainability” and invites high-quality submissions covering topics including but not limited to:

- **modeling for sustainability and sustainability of modeling**
- technical sustainability: systems models (evolution, techniques promoting good practices lifecycle conformance to environmental sustainability) energy consumption of modeling, modeling and simulation of energy consumption
- social sustainability: ethical concerns and modelling-based decision support sustainability: equality and cost trade-offs, cost effective methods
- frameworks and tools
- open-source frameworks and model libraries
- decision support for sustainability: ordinal models and ordinal models
- industry 4.0 and sustainability-driven design
- sustainable and secure system engineering
- empirical impact analysis, case studies, tool evaluations
- training and education, especially on the topic of developing the next generation of systems engineering professionals.
How to simulate sustainability scenarios within digital twins?

How to model connections between sustainability indicators?

How to model sustainability requirements?

How to improve the automation of sustainability assessment?

How to assess sustainability for socio-technical systems?

How to balance sustainability requirements and SW quality requirements in DT engineering?

Which metrics are relevant for measuring sustainability of DTs?

How to map low-level sustainability requirements of actual systems to high-level SDGs?

How to simulate sustainability scenarios within digital twins?
**LET US GO CRAZY...**

go crazy on digital twin research with an impact

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

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