Software Sustainability and its Engineering:
How far have we come?

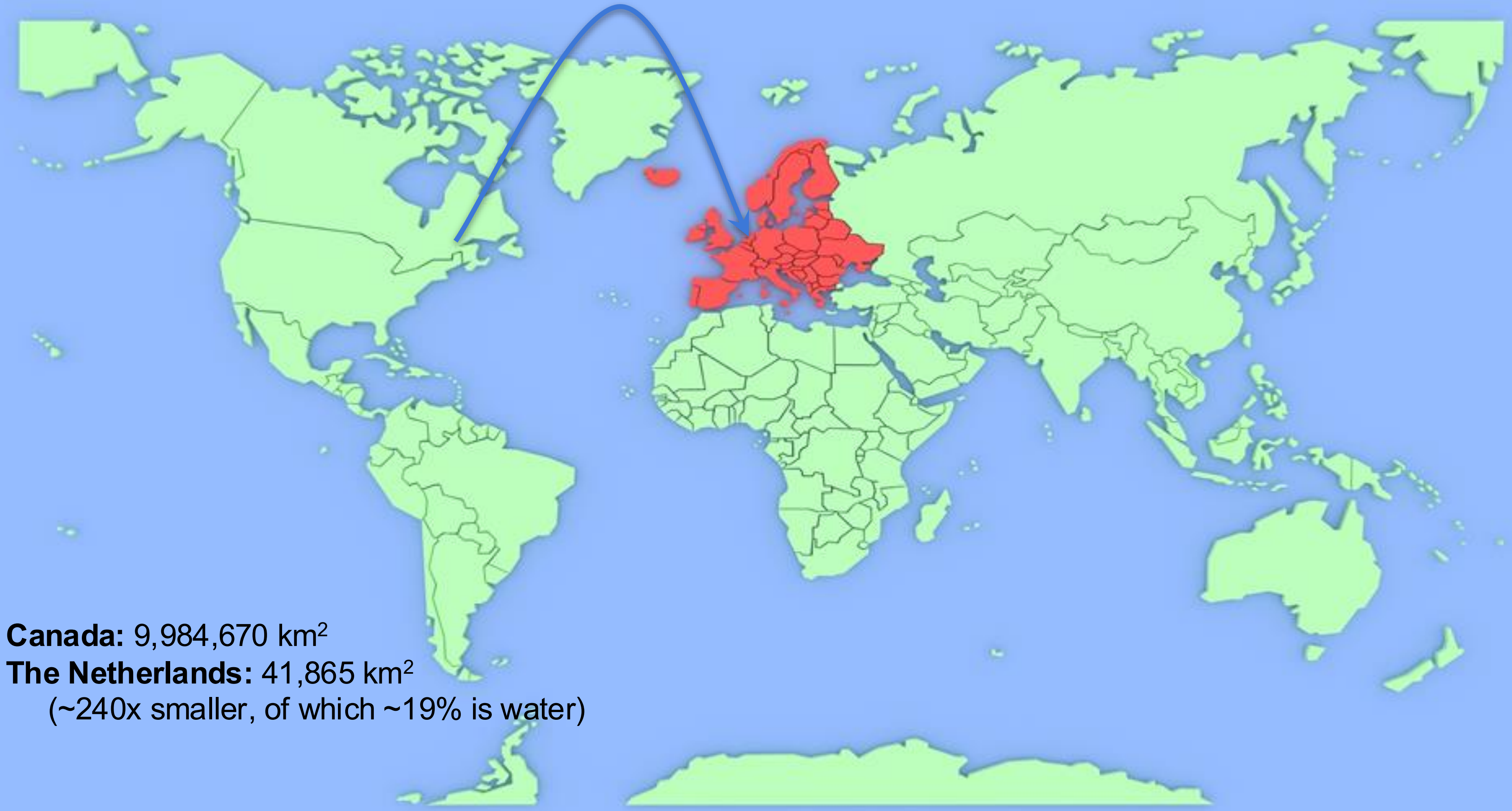
Patricia Lago
Vrije Universiteit Amsterdam

SOFTWARE AND SUSTAINABILITY
S2 RESEARCH GROUP

DIGITAL SUSTAINABILITY CENTER

VU VRIJE UNIVERSITEIT AMSTERDAM

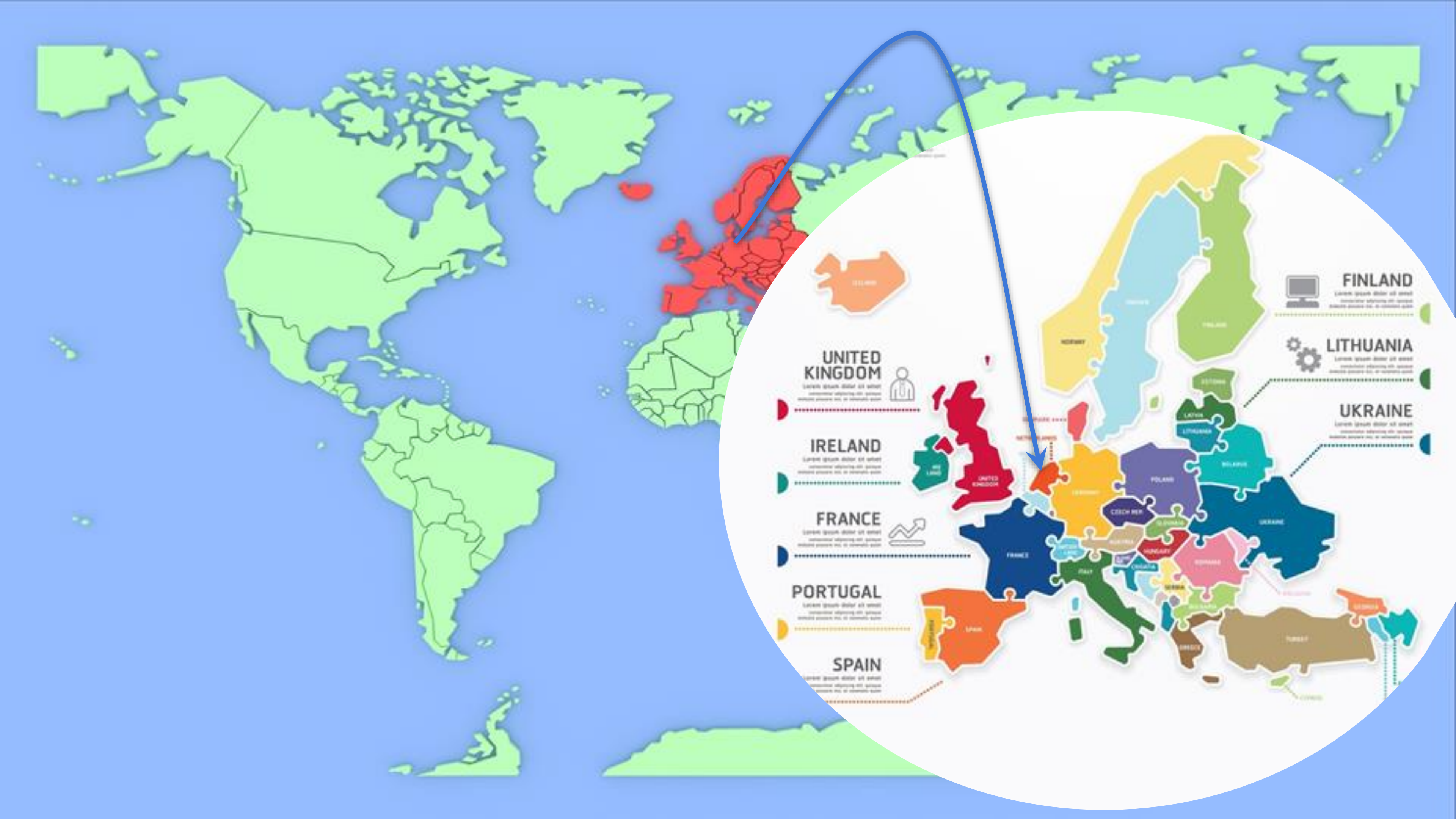
a disclaimeR



Canada: 9,984,670 km^2

The Netherlands: 41,865 km^2

(~240x smaller, of which ~19% is water)



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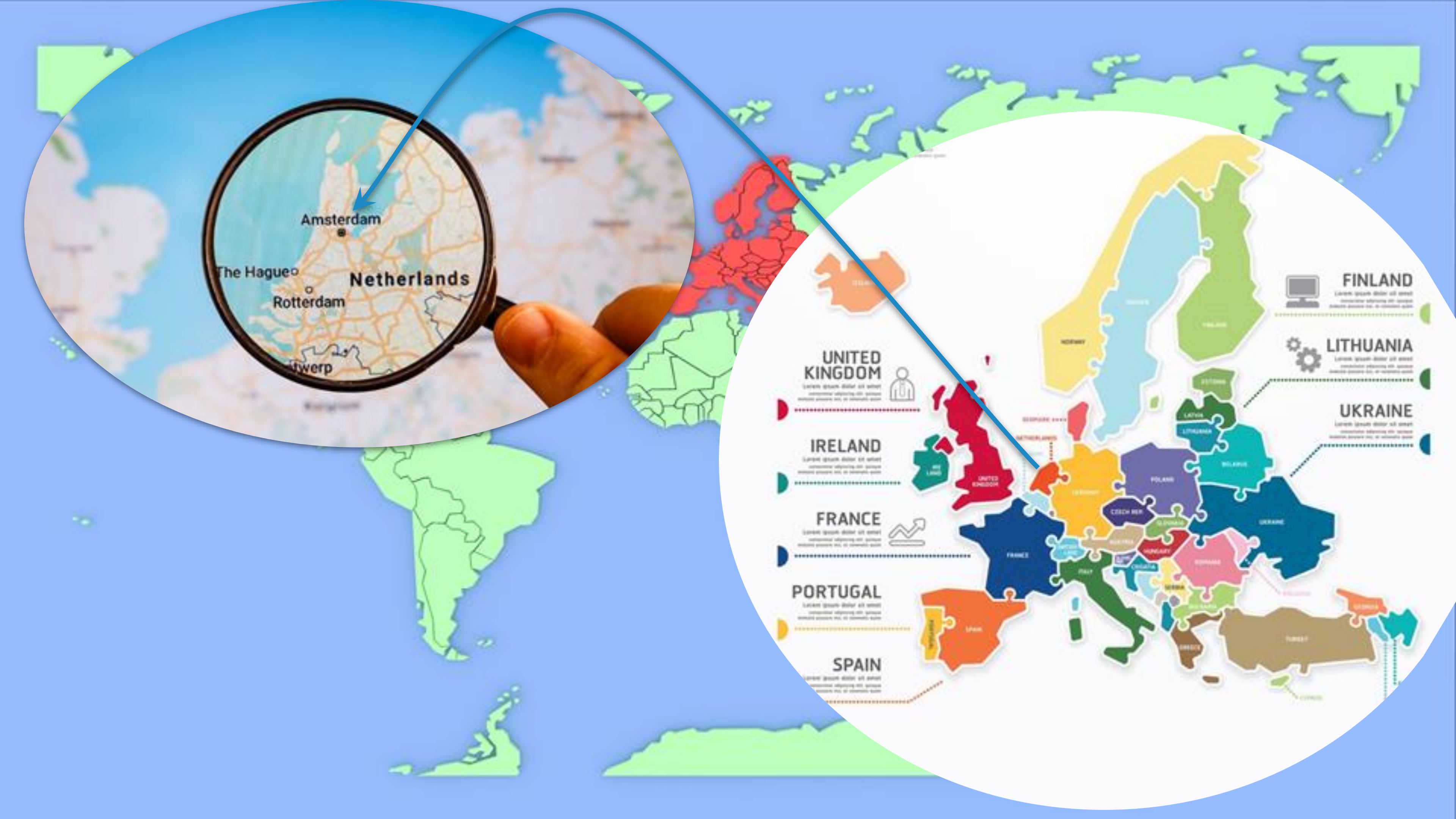
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Strand IJburg
DE AKER
NIEUW SLOTEN
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OVERAMSTEL
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Badhoevedorp
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Vrije Universiteit Amsterdam - VU Amsterdam - Zuidas

Discover our Campus
NU University Building

32,000 STUDENTS
4800 EMPLOYEES
139 BSC/MSC PROGRAMS

7 FACULTIES
24 INTERDISCIPLINARY INSTITUTES

Vrije Universiteit Amsterdam - VU Amsterdam - Zuidas

Research that matters

The S2 group @ VU Amsterdam

s2group.cs.vu.nl


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Dr. Emitzá Guzmán
Assistant Professor


Dr. Ilias Gerostathopoulos
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Dr. Justus Bogner
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Tom Humbert
PhD Student


Keerthiga Rajenthiram
PhD Student

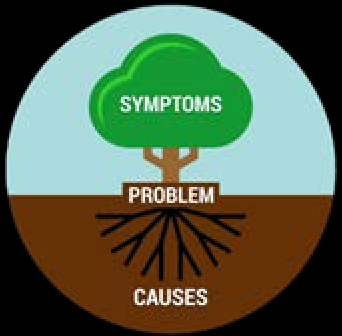

Rumbidzai Chitakunye
PhD Student

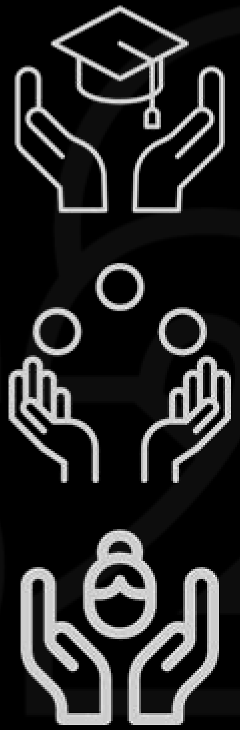

Engelbert Fellinger
PhD Student


Bouazza El Moutaouakil
PhD Student

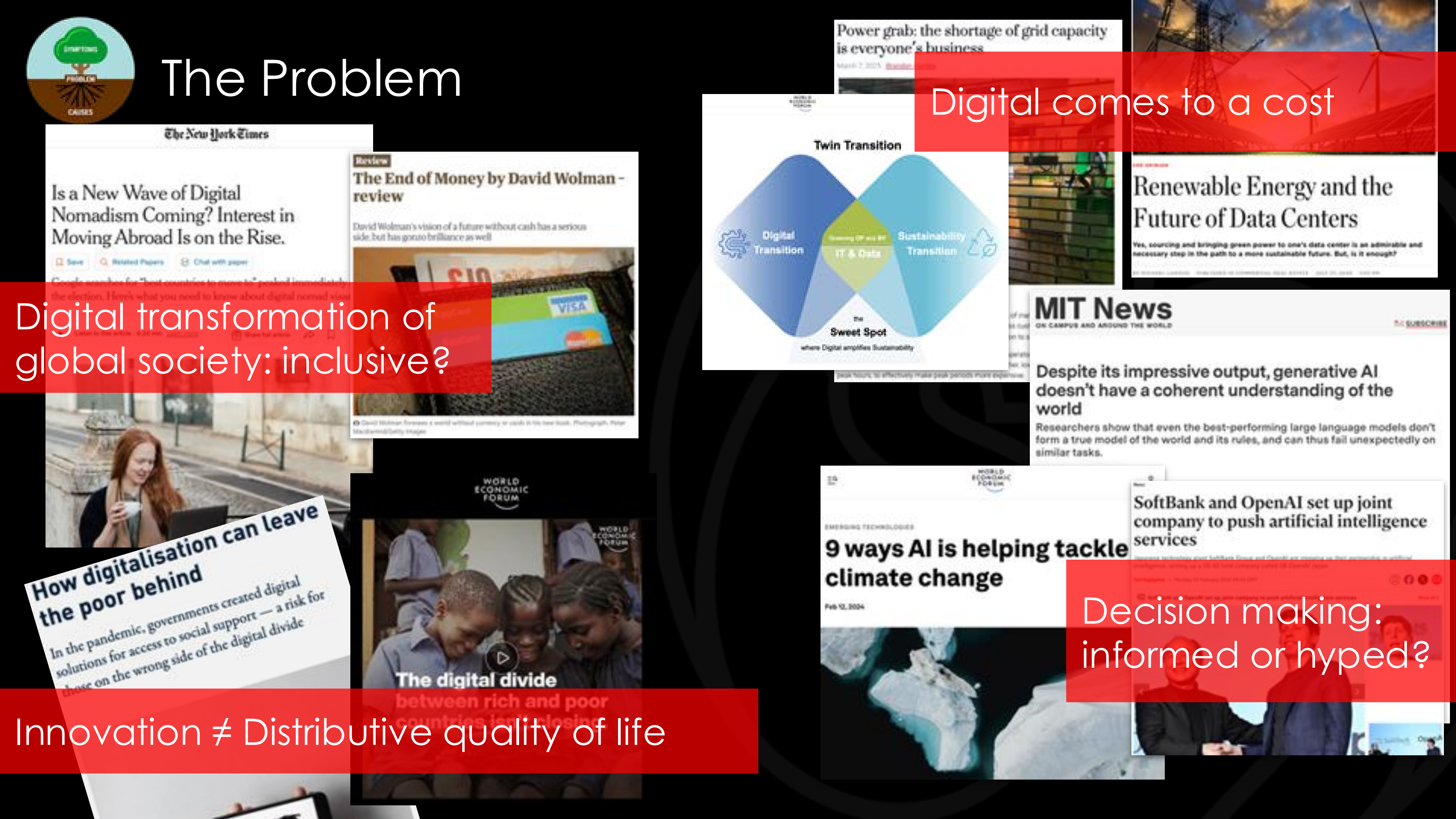

Muhammad Imran
Guest PhD Student

The flow





The Problem



Digital transformation of global society: inclusive?

Digital comes to a cost

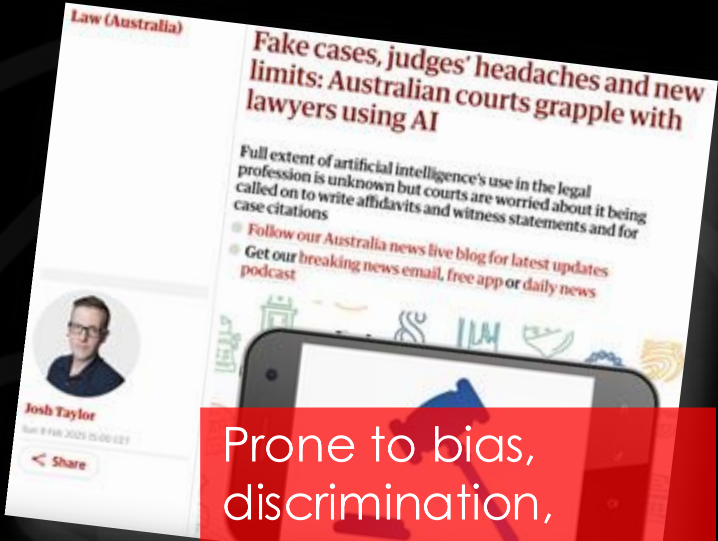
Decision making: informed or hyped?

Innovation ≠ Distributive quality of life

The Symptoms

Planet Earth rebels

Prone to bias, discrimination, misuse



Misinformation and disinformation, Adverse outcomes of AI technologies

The Causes

We must take action

*"I have witnessed **large parts of society** turn their heads and deliberately **reject the truths that have been presented to them**. The rise of unreason has been the unwelcome partner to our growing scientific sophistication."* [Robin McKie, Science editor, the Observer]

Denial

–

Feeling Powerless

*"You know, we all feel like **the system is too big to change, but guess what? We are the system**, and we need to change."* [Dr. Goodwin, New Amsterdam, Netflix series]

We can take action

The past: where do we come from?

Sustainability in general

Dimensions

https://tinyurl.com/y3cfecs4

ID 181173892 © Alain Lacroix | Dreamstime.com

ESG

https://en.wikipedia.org/wiki/Environmental,_social,_and_governance

Order of impacts

DIRECT IMPACT
(technology)

SYSTEMIC IMPACT
(change in behavior)

ENABLING IMPACT
(supported processes)

F. Berkhout and J. Hertin, "Impacts of information and communication technologies on environmental sustainability: Speculations and evidence," Report to the OECD, Brighton, vol. 21, p. 23, 2001. (archived)

UN Sustainable Development Goals

https://sdgessentials.org/why-the-world-needs-the-sdgs.html

Software sustainability:
a definition

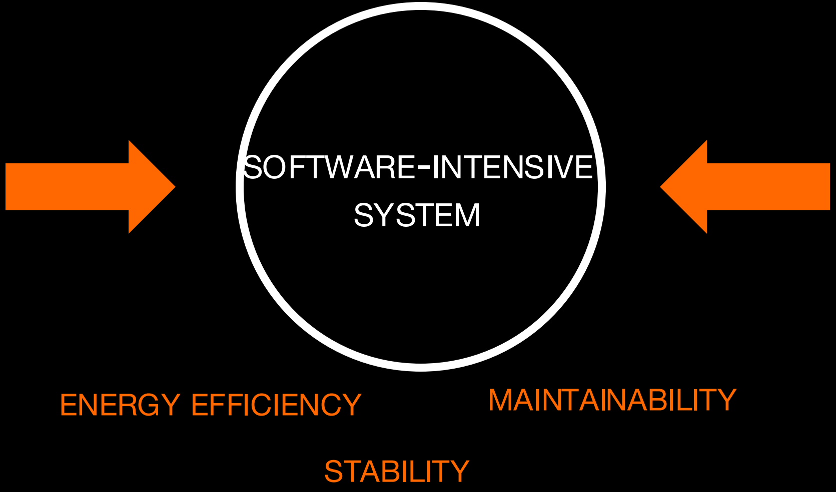
1) … the "capacity to **endure**" – from UN Brundtland Report: Our Common Future (1987)
2) … the "**preservation of the function of a system** over an **extended period of time**" – Lago & Penzenstadler (2017). Editorial: Reality check for software engineering for sustainability—pragmatism required. Journal of Software: Evolution and Process, 29(2).
3) … the "**balance**" among relevant dimensions - and the relationship between micro-level actions and macro-level impacts [1]

Software sustainability is the preservation of the long-term and beneficial use of software, and its appropriate evolution, in a context that continuously changes [2]

[1] L.M. Hilty and B. Aebischer (2015), "ICT for Sustainability: An Emerging Research Field," in ICT Innovations for Sustainability, Springer, pp. 3–36.
[2] Lago, P. (2023). The Digital Society Is Already Here – Pity It Is 'Unsustainable'. In I. Vermeulen (Ed.), Connected World: Insights from 100 Academics on How to Build Better Connections VU University Press Amsterdam.

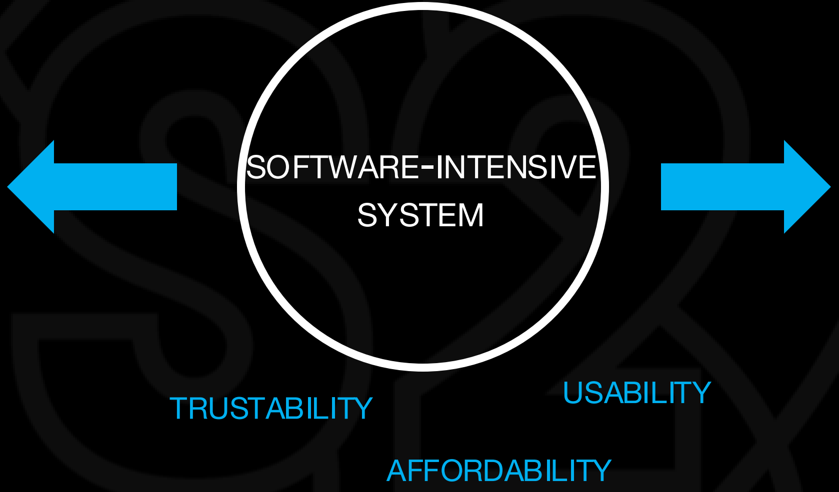
The role of software in sustainability:
two perspectives

Inward looking



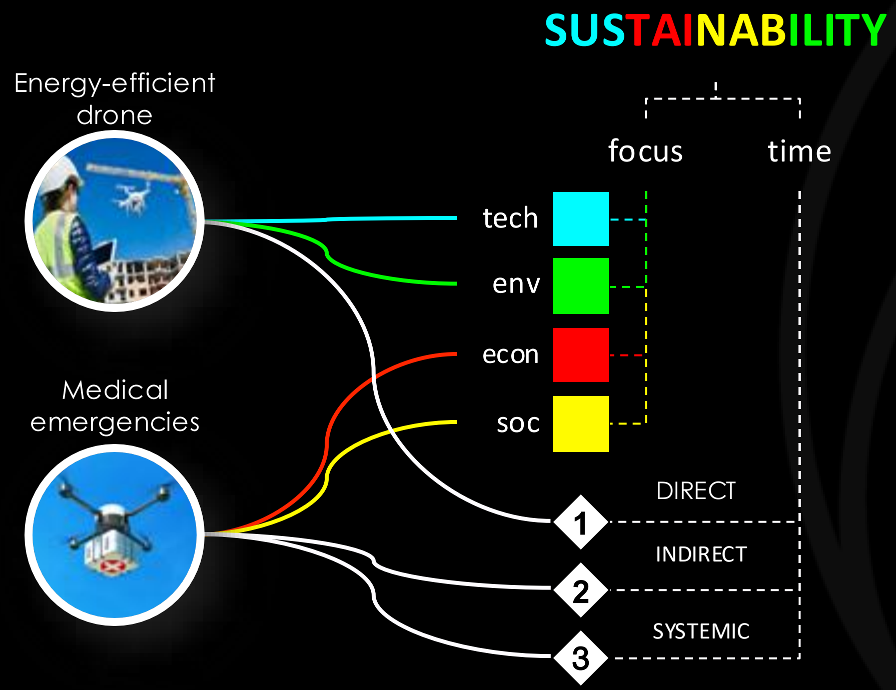
Direct impact
(sustainable software)

Outward looking



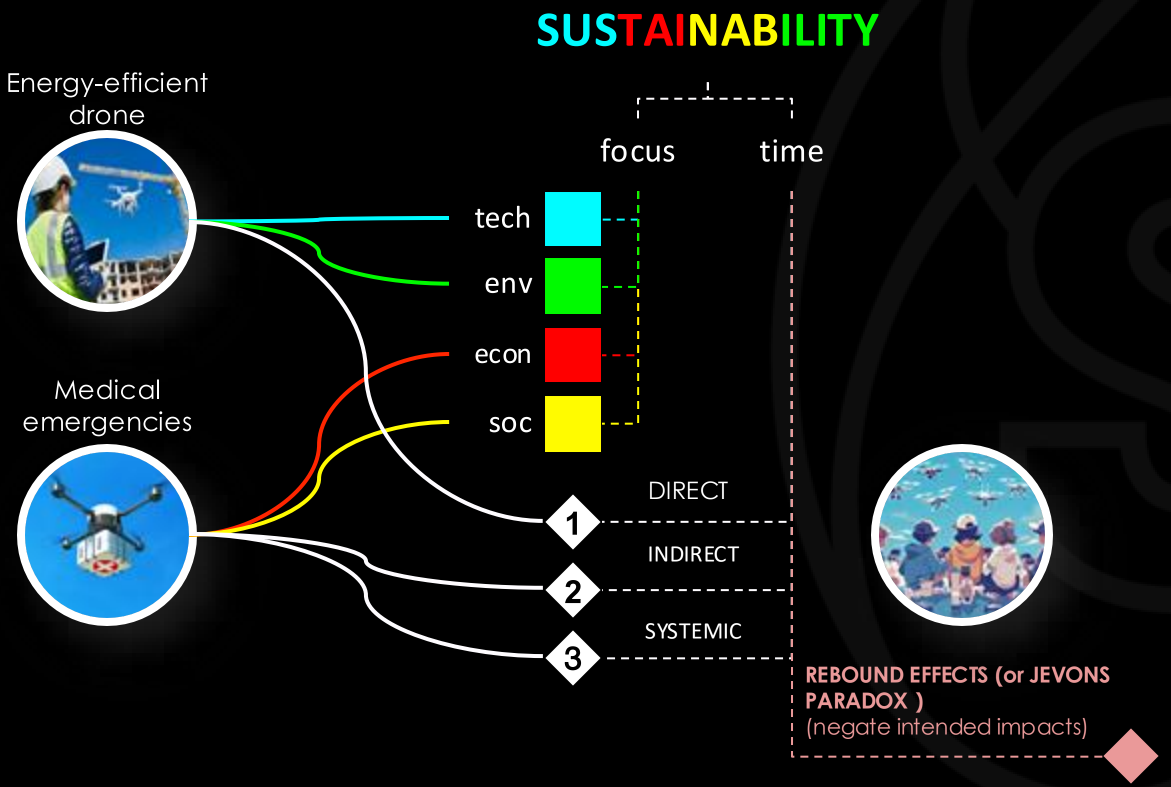
Indirect impact
(software for sustainability)

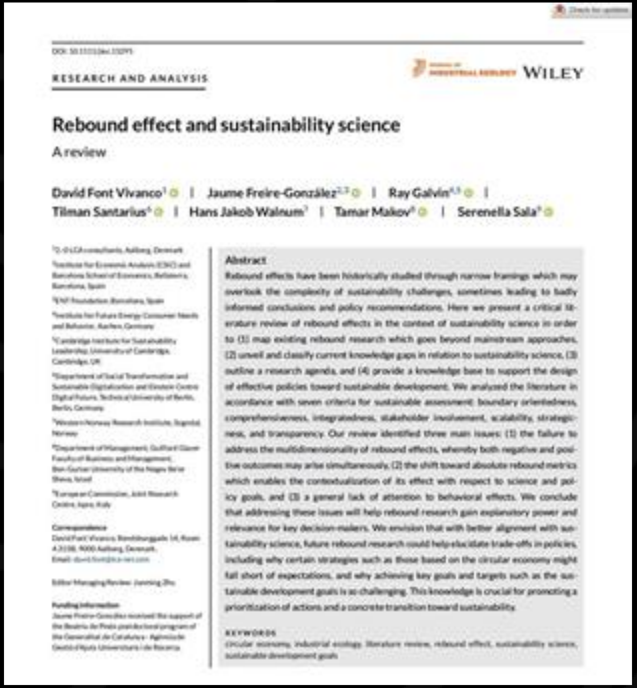
The role of software in sustainability:
dimensions of **focus**, dimensions of **time**



The role of software in sustainability:

dimensions of **focus**, dimensions of **time**, and **rebound effects**





RESEARCH AND ANALYSIS

WILEY

Rebound effect and sustainability science

A review

David Font Vivanco | Jaume Freire-González | Ray Galvin | Tilman Santarius | Hans Jakob Walnum | Tamar Makov | Serenella Sala

Abstract

Rebound effects have been historically studied through narrow framings which may overlook the complexity of sustainability challenges, sometimes leading to badly informed conclusions and policy recommendations. Here we present a critical literature review of rebound effects in the context of sustainability science in order to (1) map existing rebound research which goes beyond mainstream approaches, (2) unveil and classify current knowledge gaps in relation to sustainability science, (3) outline a research agenda, and (4) provide a knowledge base to support the design of effective policies toward sustainable development. We analyzed the literature in accordance with seven criteria for sustainable assessment: boundary orientedness, comprehensiveness, integratedness, stakeholder involvement, scalability, strategicness, and transparency. Our review identified three main issues: (1) the failure to address the multidimensionality of rebound effects, whereby both negative and positive outcomes may arise simultaneously, (2) the shift toward absolute rebound metrics which enables the contextualization of its effect with respect to science and policy goals, and (3) a general lack of attention to behavioral effects. We conclude that addressing these issues will help rebound research gain explanatory power and relevance for key decision-makers. We envision that with better alignment with sustainability science, future rebound research could help elucidate trade-offs in policies, including why certain strategies such as those based on the circular economy might fall short of expectations, and why achieving key goals and targets such as the sustainable development goals is so challenging. This knowledge is crucial for promoting a prioritization of actions and a concrete transition toward sustainability.

KEYWORDS

circular economy, industrial ecology, literature review, rebound effect, sustainability science, sustainable development goals

The role of software in sustainability:
Digital sufficiency

Policies reducing the need for **HW** and **SW** (e.g., the right to repair)

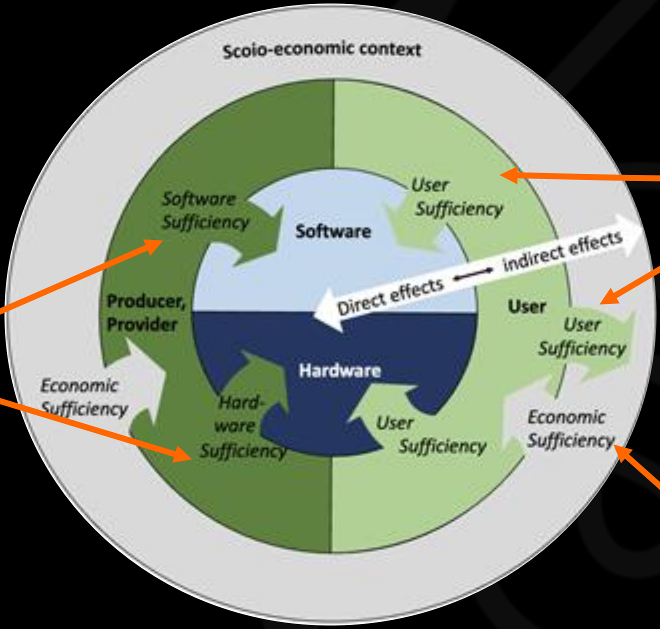


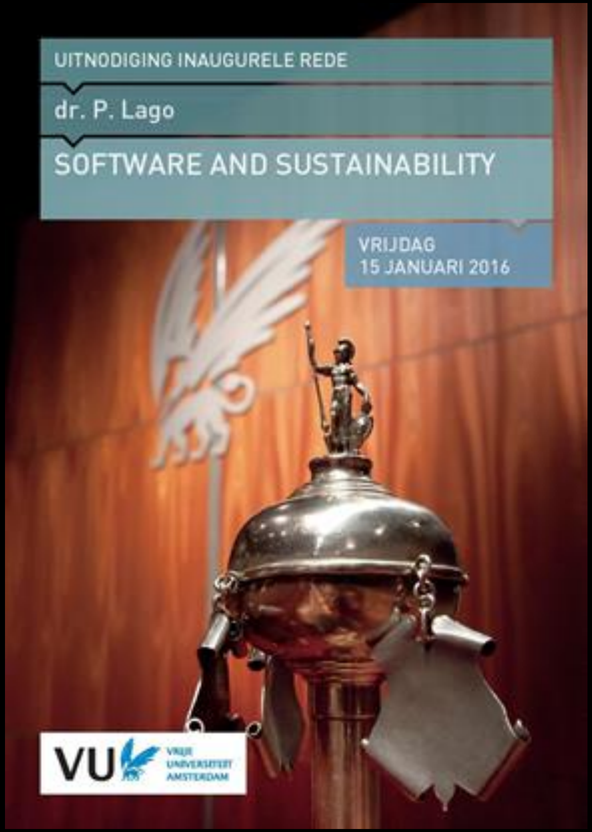
*Fig. 1: Interplay of the four dimensions of digital sufficiency

Policies empowering the **user** in how ICT is used (e.g., focus) and for what purpose (e.g., collaboration)

Policies fostering an **economy** that addresses societal and individual needs (rather than growth) (e.g., reducing avg working hours)

- (*) T. Santarius et al., "Digital sufficiency: conceptual considerations for ICTs on a finite planet," Ann. Telecommun., vol. 78, no. 5–6, pp. 277–295, 2023.
- L. Hilty, "Computing Efficiency, Sufficiency, and Self-sufficiency: A Model for Sustainability?," in Computing with Limits, Irvine, CA, USA, 2015.

The present: how far did we come?

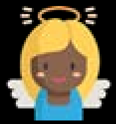


The present: how far did we come?



	The good	The bad	The mystery
Notion of sustainability	DIMENSIONS OF FOCUS	DIMENSIONS OF TIME HUMAN FACTORS	ROLE OF CONTEXT
Sustainability-aware sw/SE	TECHNOLOGY	KNOWLEDGE SYNTHESIS MEASURES	EDUCATION AND TRAINING
Sustainability-aware sw architecting/SA	DESIGN DECISION MAKING	QUALITY ASSESSMENT	SYSTEMIC DESIGN TRACEABILITY

The present: how far did we come?



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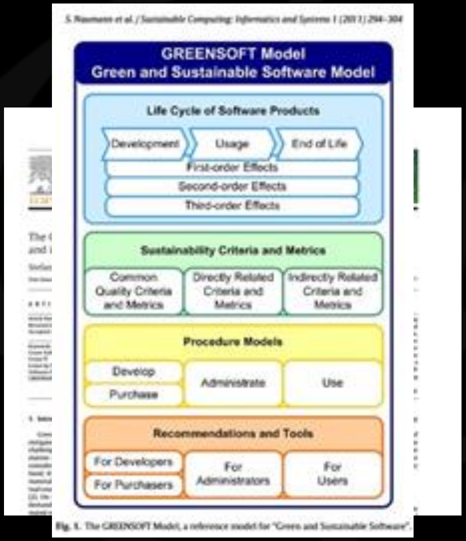
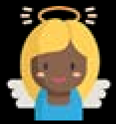


GREENSOFT reference model (2011)

4D sw sustainability (at ICSE GREENS 2013, Published in 2015)

The present: how far did we come?


The good


The bad


The mystery

	The good	The bad	The mystery
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Sustainability Awareness Framework (SusAF)

Lessons Learned from Developing a Sustainability Awareness Framework for Software Engineering Using Design Science

STEFANIE BETZ, Furtwangen University and LUT University, Furtwangen, Germany
BIRGIT PENZENSTADLER, Chalmers University of Technology and LUT University, Gothenburg, Sweden
LETICIA DUBOC, La Salle, University Ramon Llull, Barcelona, Spain
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Sustainability Assessment Framework (SAF) Toolkit

Software and Systems Modeling
https://doi.org/10.1007/s10270-024-01230-9

THEME SECTION PAPER

The sustainability assessment framework toolkit: a decade of modeling experience

Patricia Lago[1] · Nelly Condori Fernandez[2] · Iffat Fatima[1] · Markus Funke[1] · Ivano Malavolta[1]

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Abstract
Software intensive systems play a crucial role in most, if not all, aspects of modern society. As such, both their sustainability

The present: how far did we come?

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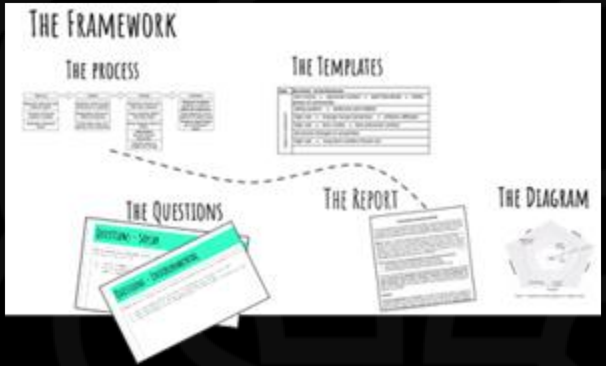
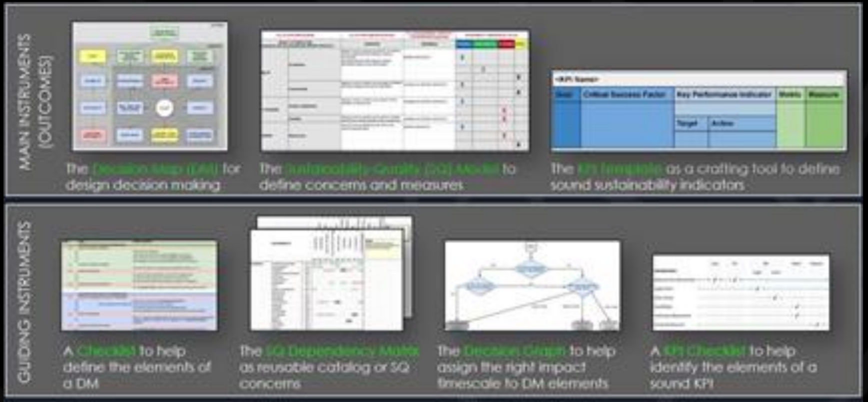
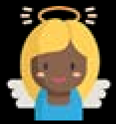
Sustainability Awareness Framework (SusAF)



Sustainability Assessment Framework (SAF) Toolkit



The present: how far did we come?



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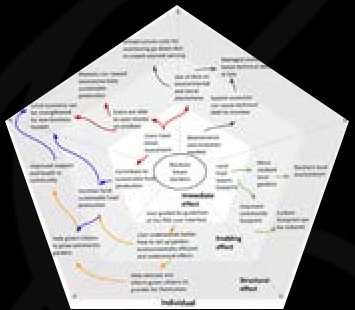
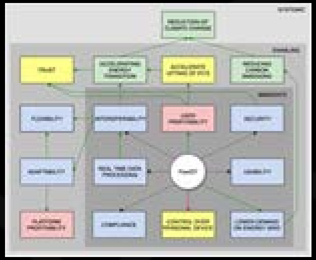



Three time horizons: more an intuition than a solution

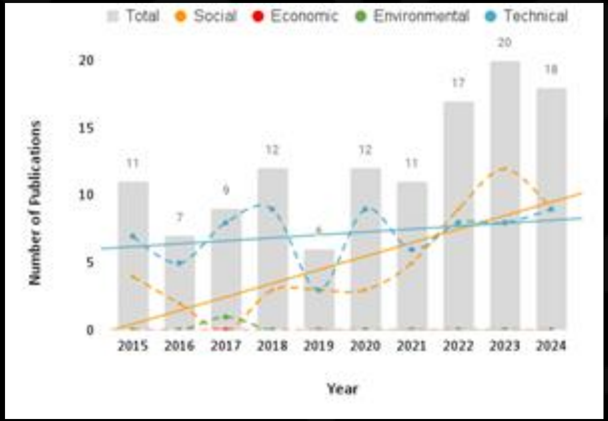


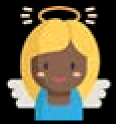
Fig.4. Direct focus of SEIS publications over the years (*)

72/123 50/123
1/123 0/123

Human factors as an established QA
Not really about sustainability, but rather societal implications

(*) I. Fatima and P. Lago (2025), “Ten Years of Software Engineering in Society,” in International Conference on ICT for Sustainability (ICT4S), IEEE. To appear.

The present: how far did we come?



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- *Experiments: well designed and executed?*
- *Results: well described (and not over-stated)?*
- *Lessons learned: synthesized and made available?*

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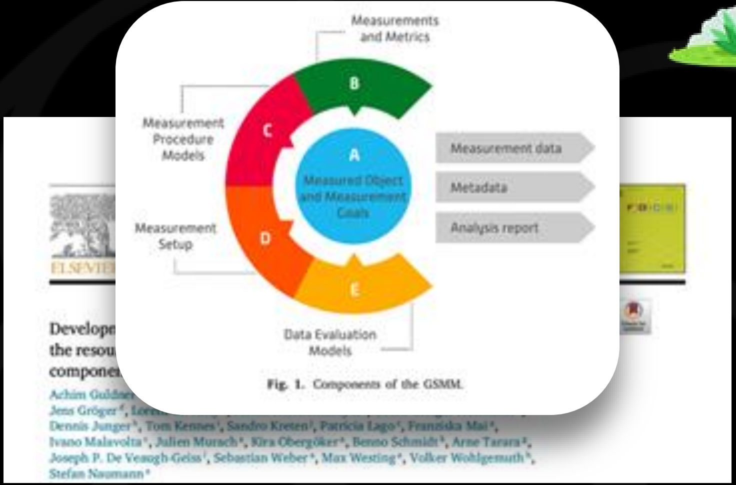


Fig. 1. Components of the GSMM.

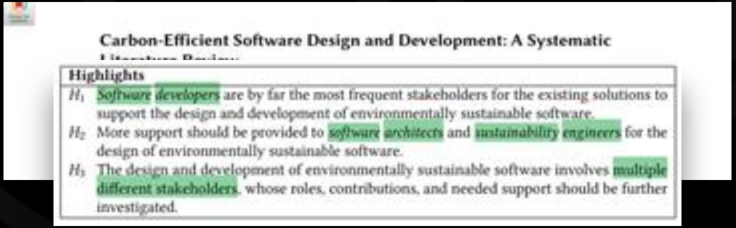
Achim Guldner, Jens Gröger, Dennis Junger, Tom Kennes, Sandro Kreten, Patricia Lago, Franziska Mai, Ivano Malavolta, Julien Murach, Kira Obergöker, Benno Schmidt, Arne Tarara, Joseph P. De Veaugh-Geiss, Sebastian Weber, Max Westing, Volker Wohlgemuth, Stefan Naumann

Green Software Measurement Model (GSMM)


Ten Years of Teaching Empirical Software Engineering in the Context of Energy-Efficient Software

Ivano Malavolta, Vincenzo Stoico, and Patricia Lago

Sound experiments


Carbon-Efficient Software Design and Development: A Systematic Literature Review

Highlights

H_1 Software developers are by far the most frequent stakeholders for the existing solutions to support the design and development of environmentally sustainable software.

H_2 More support should be provided to software architects and sustainability engineers for the design of environmentally sustainable software.

H_3 The design and development of environmentally sustainable software involves multiple different stakeholders, whose roles, contributions, and needed support should be further investigated.

Beyond sw developers

The present: how far did we come?

AS RESEARCHERS, WHAT SOCIETAL IMPACT DO WE WANT TO CREATE?

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Green Software Foundation

SUSTAINABLEIT.ORG

IASA

SDIA

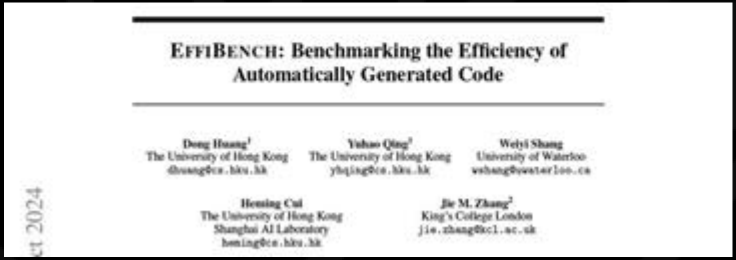
add scientific rigour; share good practices

OPEN ARCHIVE (REUSABLE TACTICS)

ISO IEC — Software Carbon Intensity (SCI)

ISO DIN — Resource-efficient software

- "Improve" over "use"
- Sound metrics, comparable measures



EFFIBENCH: Benchmarking the Efficiency of Automatically Generated Code

Dong Huang[1] The University of Hong Kong [illegible]
Yuhao Qing[1] The University of Hong Kong yhqing@cs.hku.hk
Weiyi Shang University of Waterloo wshang@uwaterloo.ca
Heming Cui The University of Hong Kong Shanghai AI Laboratory heming@cs.hku.hk
Jie M. Zhang[2] King's College London [illegible]

ct 2024

Benchmarks

The present: how far did we come?

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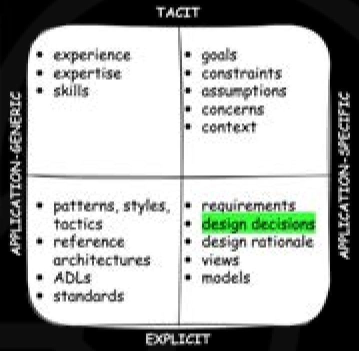
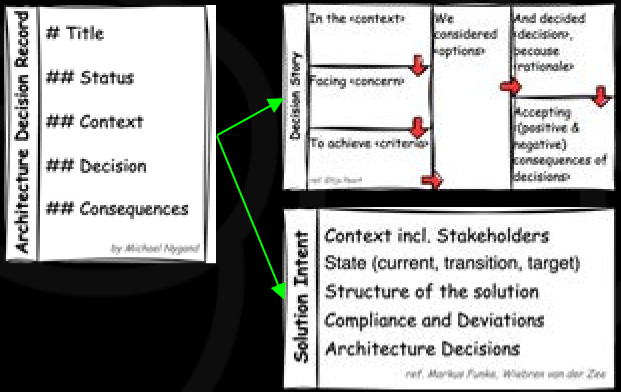
Standards work very well (thus far)[1]



Simple
Beneficial
Useable[2]



@CGI

@ABN AMRO

- [1] ISO/IEC/IEEE 42010:2022 including ethical and sustainability concerns
- Architectural Decision Records https://adr.github.io/
- [2] J. Maeda, The Laws of Simplicity. MIT Press, 2006.

The present: how far did we come?


The good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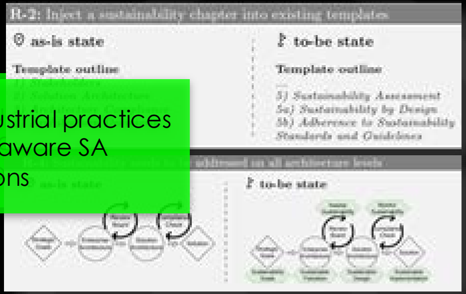


From SoTA+ industrial practices **to** sustainability-aware SA recommendations

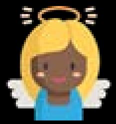
- M. Funke and P. Lago, “Carving Sustainability into Architecture Knowledge Practice,” in European Conference on Software Architecture (ECSA), LNCS, vol. 14212. Springer, 2023.
- Sustainable IT Lab VU-ABNAMRO: https://digitalsustainabilitycenter.nl/pages/vu-abn-lab

From industry context **to** sustainability-aware design decisions

- Precision and recall
- Resource-efficiency
- 4,911 ADRs, autom. metrics, human evals
- SLMs = small devices, in-house

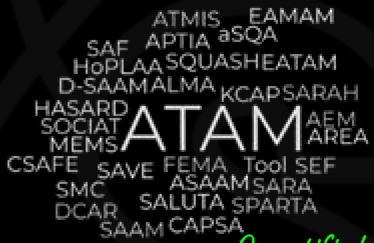
- R. Dhar, K. Vaidhyanathan, and V. Varma, “Can LLMs generate architectural Design Decisions? An exploratory empirical study,” in ICSA 2024, IEEE.
- –, (follow-up study upcoming)
- ArchBench: LLMs for Software Architecture Tasks. https://www.sabench.com

The present: how far did we come?



	The good	The bad	The mystery
Notion of sustainability	DIMENSIONS OF FOCUS	DIMENSIONS OF TIME HUMAN FACTORS	ROLE OF CONTEXT
Sustainability-aware sw/SE	TECHNOLOGY	KNOWLEDGE SYNTHESIS MEASURES	EDUCATION AND TRAINING
Sustainability-aware sw architecting/SA	DESIGN DECISION MAKING	QUALITY ASSESSMENT	SYSTEMIC DESIGN TRACEABILITY

Sustainability can be represented by quality attributes (QAs) that have impacts across multiple dimensions[1]

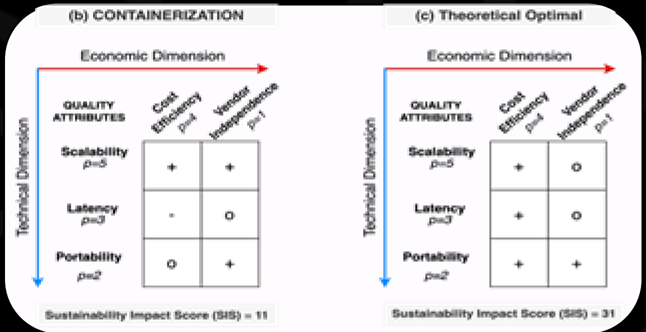


SA evaluation blueprint [2]

- *Multiple dimensions of focus*
- *Multiple QAs in Sust. Indicators*

Sustainability Impact Score (SIS)

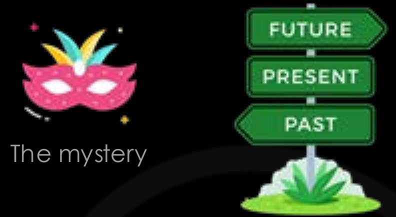
Quantified trade-offs between Sust. Dimensions[3]

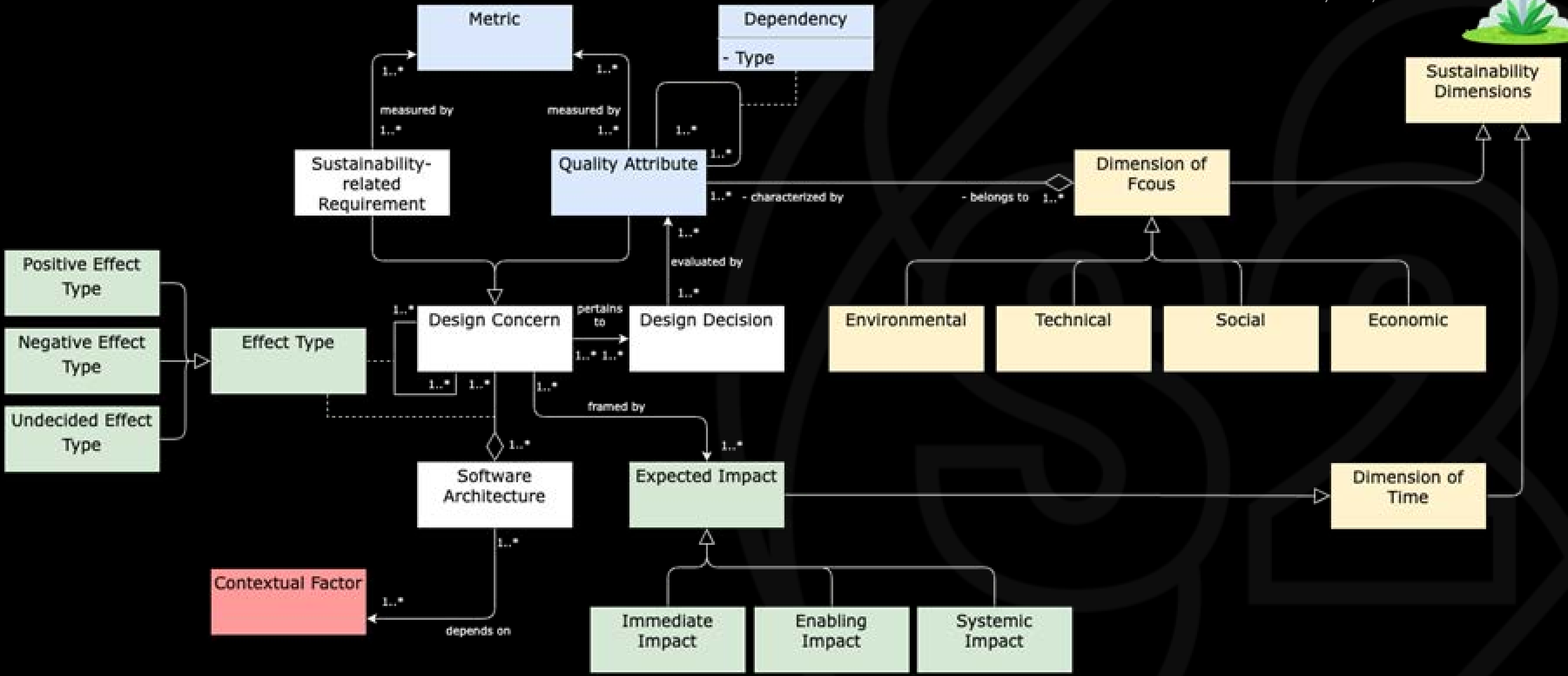


[1] N. Condori-Fernandez, et.al, "An Action Research for Improving the Sustainability Assessment Framework Instruments. In Sustainability, 12(4), 2020.
[2] I. Fatima and P. Lago, "Towards a sustainability-aware software architecture evaluation for cloud-based software services," in ECSA 2024 D. Symp, Springer.
[3] I. Fatima, P. Lago, V. Andrikopoulos, B. v.d. Waaij, "Using sustainability impact scores for software architecture evaluation," in ICSA 2025, IEEE.

The (desirable) future: where should we go?

Systemic design

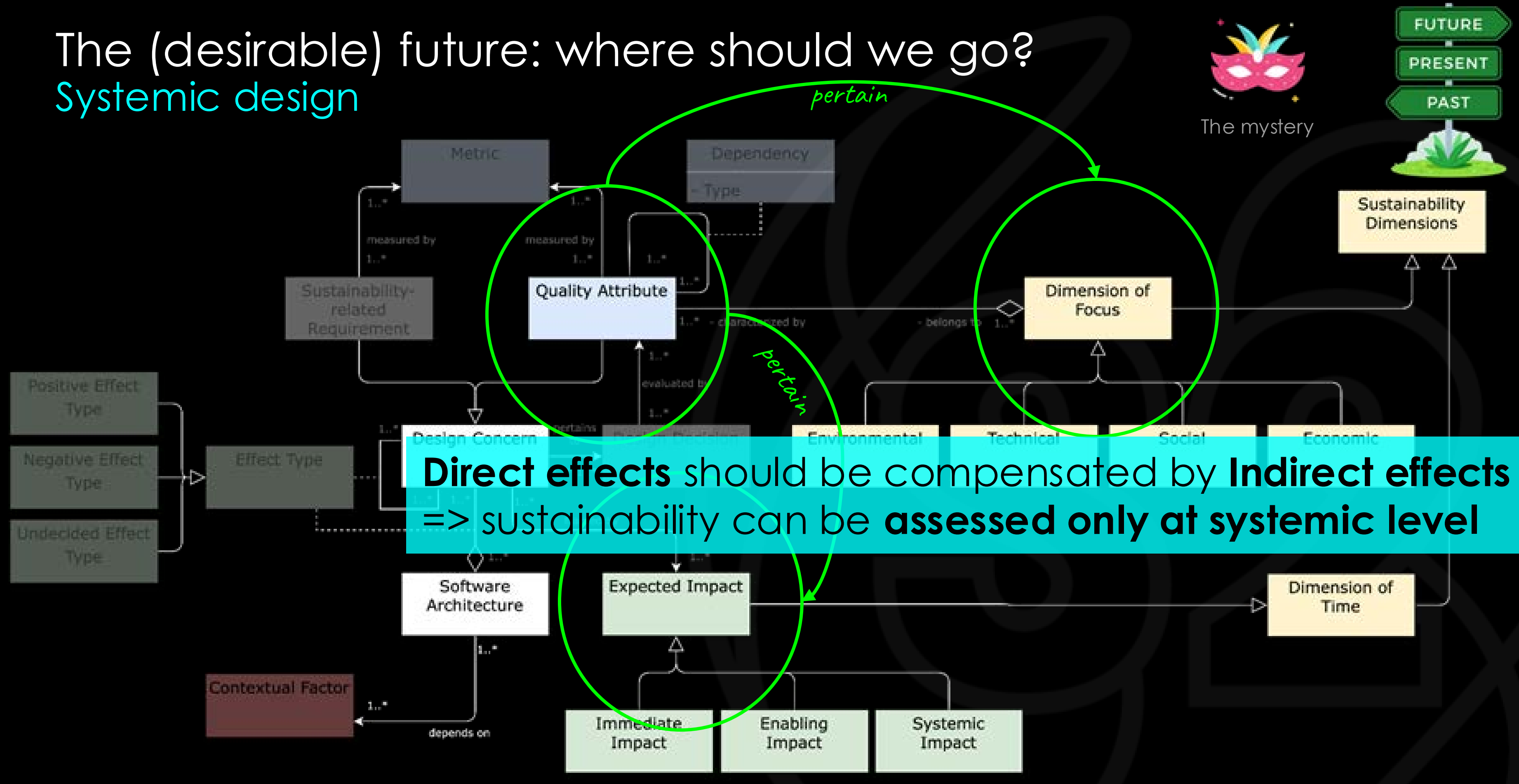




P. Lago, N. C. Fernandez, I. Fatima, M. Funke, and I. Malavolta, "The Sustainability Assessment Framework Toolkit: A Decade of Modeling Experience," Softw. Syst. Model., 2024, doi: 10.1007/s10270-024-01230-9. ArXiv https://arxiv.org/abs/2405.01391v2

The (desirable) future: where should we go?

Systemic design



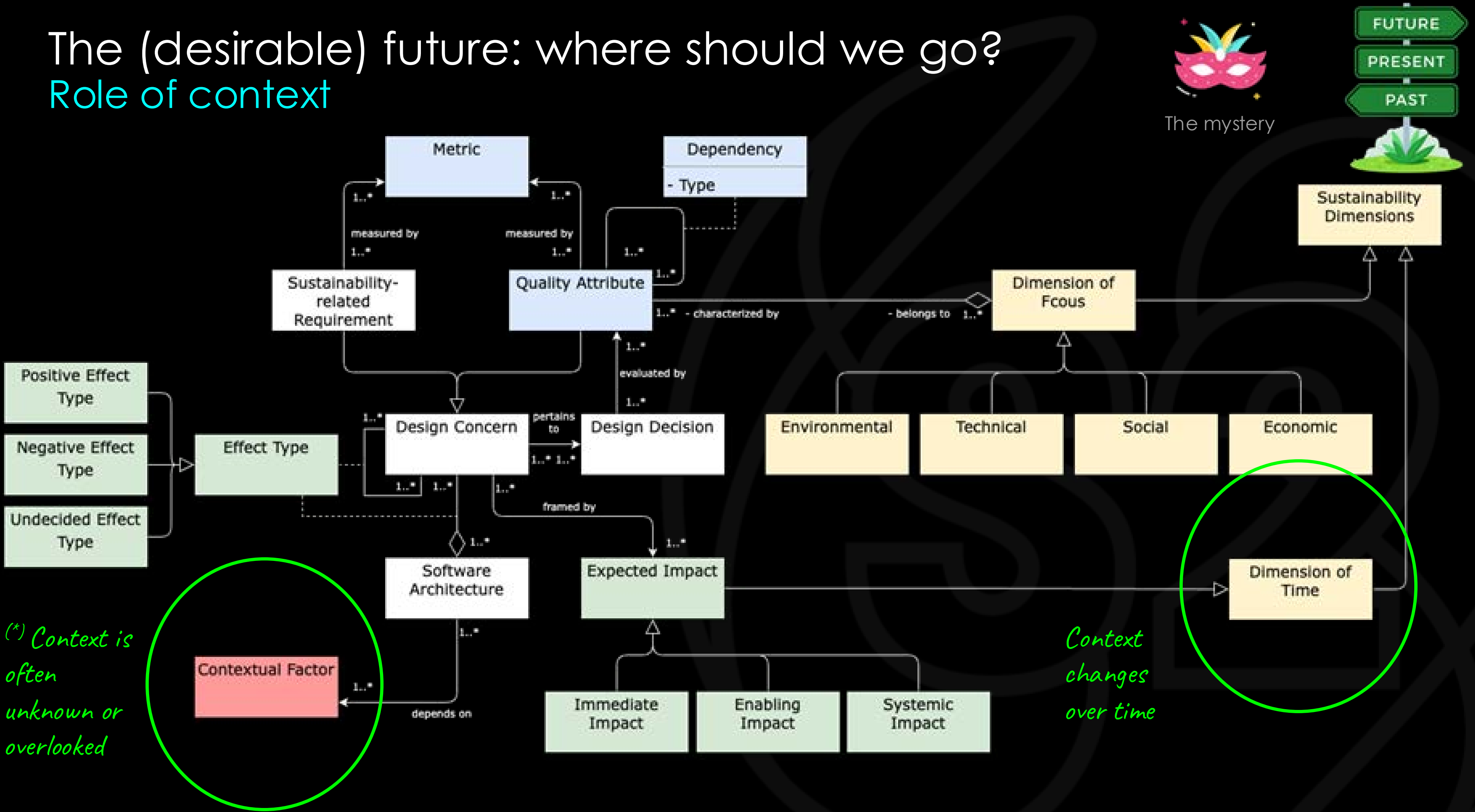
Direct effects should be compensated by **Indirect effects**
=> sustainability can be **assessed only at systemic level**

{energy, power} vs. {benefits of use}

P. Lago, N. C. Fernandez, I. Fatima, M. Funke, and I. Malavolta, "The Sustainability Assessment Framework Toolkit: A Decade of Modeling Experience," Softw. Syst. Model., 2024, doi: 10.1007/s10270-024-01230-9. ArXiv https://arxiv.org/abs/2405.01391v2

The (desirable) future: where should we go?

Role of context



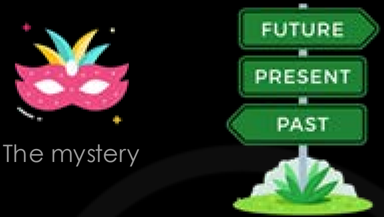
(*) Context is often unknown or overlooked

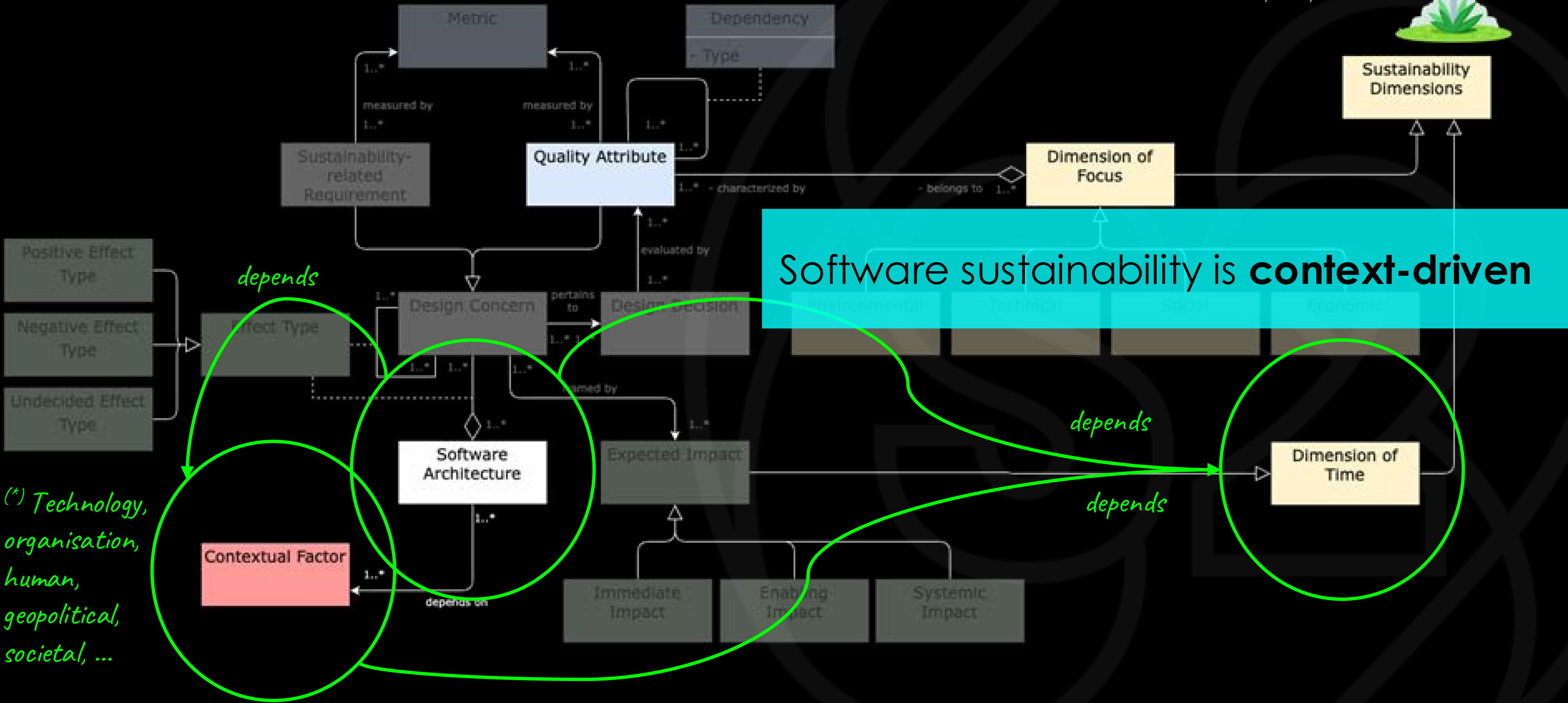
Context changes over time

(*) A. Bedjeti et al., "Modeling Context with an Architecture Viewpoint," in IEEE International Conference on Software Architecture (ICSA), IEEE, Apr. 2017.

The (desirable) future: where should we go?

Role of context





(*) L. Briand, D. Bianculli, S. Nejati, F. Pastore, M. Sabetzadeh, "The Case for Context-Driven Software Engineering Research: Generalizability Is Overrated," IEEE Softw., vol. 34(5), 2017.

The (desirable) future: where should we go?

Time and Context


The Digital Society Is Already Here –
Pity It Is 'Unsustainable'

Patricia Lago[1]

Today, digitalisation and society are intertwined t
extent that they have become wholly inseparable.
the point where large parts of society would be
function if digital systems were to fail. Think of e
visioning, traffic control, precision agriculture, o
that citizens experience first-hand like access to h
records, banking, retail shopping: all these se
heavily based on digital solutions and would not
ble any more without them. The good news, howe
thanks to digitalisation, such services are access
easily and more affordably, hence potentially serv
er chunk of the global population.

At the same time, digital systems operate global
volve multiple parties often crossing internationa
and conflicting stakes, a fact that makes them
challenging to manage. The global trend of ad
treme automation (via AI, robotics, and self-adap
nologies) both provides a solution to such cha
making digitalisation even more autonomous), an
further issues with regard to how uncontrollabl

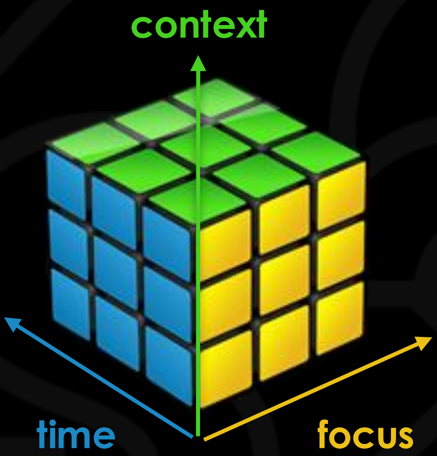
1 Patricia Lago is a professor in software engineering. She
intersection between software and sustainability.

55


Engineering Within Boundaries When Software
Has None

Bashar Nuseibeh, Member, IEEE

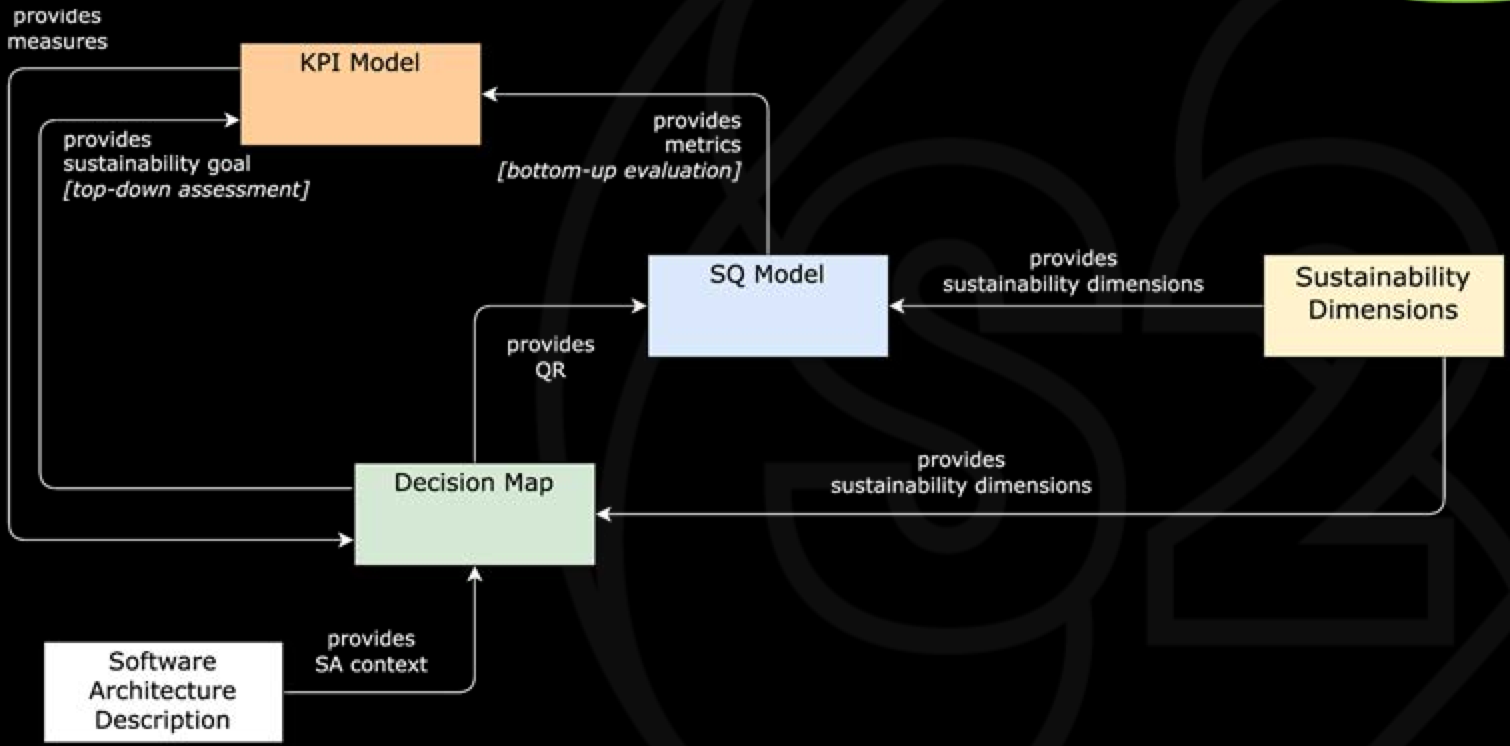
The mystery



There is no sustainability without **time** and **context**

"The responsible software engineer of the future must be the requirements engineer and the software architect of the lived experience." (Bashar Nuseibeh)

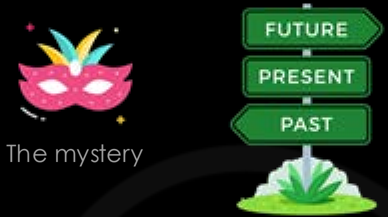
The (desirable) future: where should we go?
Traceability

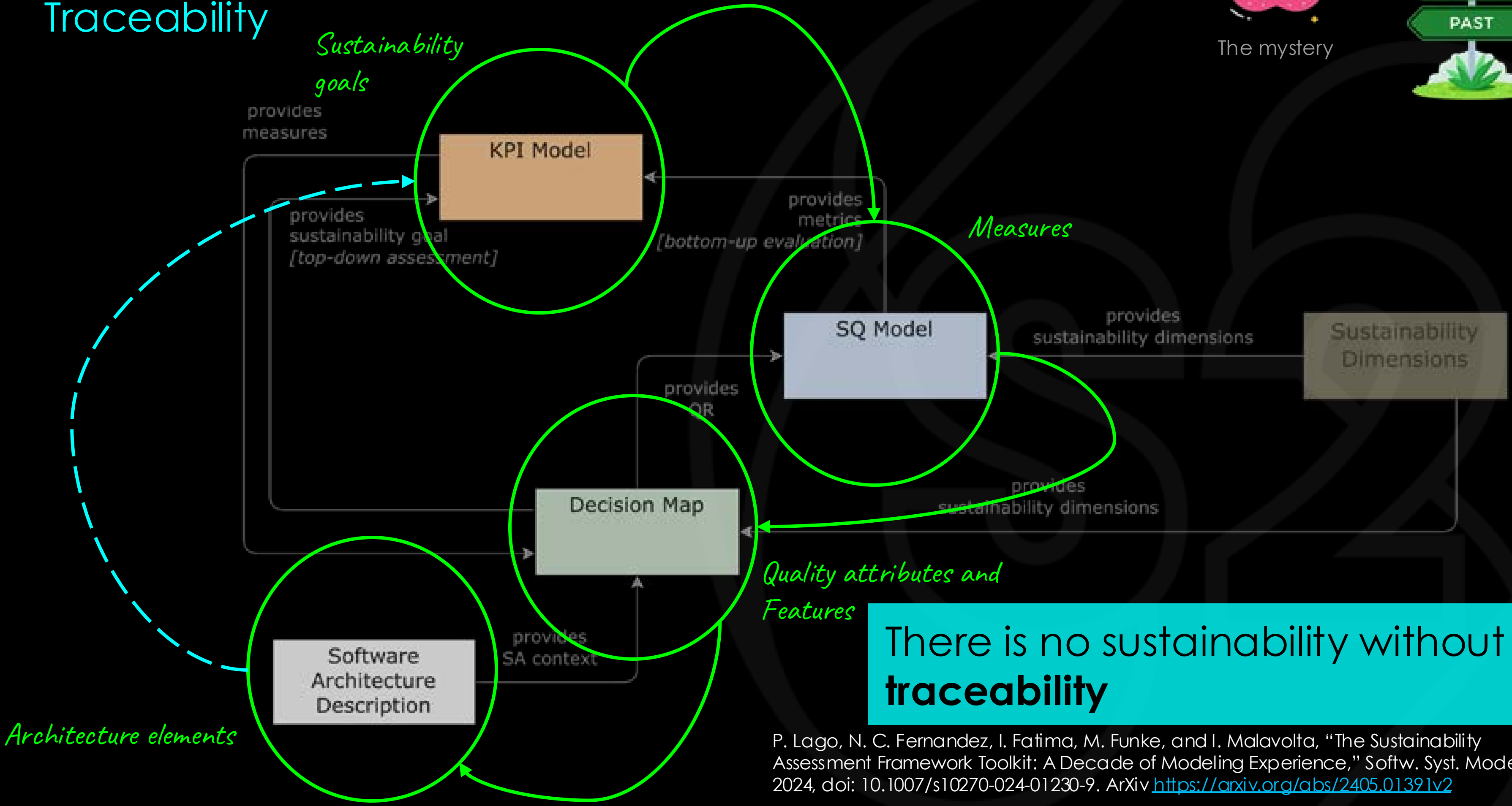


P. Lago, N. C. Fernandez, I. Fatima, M. Funke, and I. Malavolta, "The Sustainability Assessment Framework Toolkit: A Decade of Modeling Experience," Softw. Syst. Model., 2024, doi: 10.1007/s10270-024-01230-9. ArXiv https://arxiv.org/abs/2405.01391v2

The (desirable) future: where should we go?

Traceability



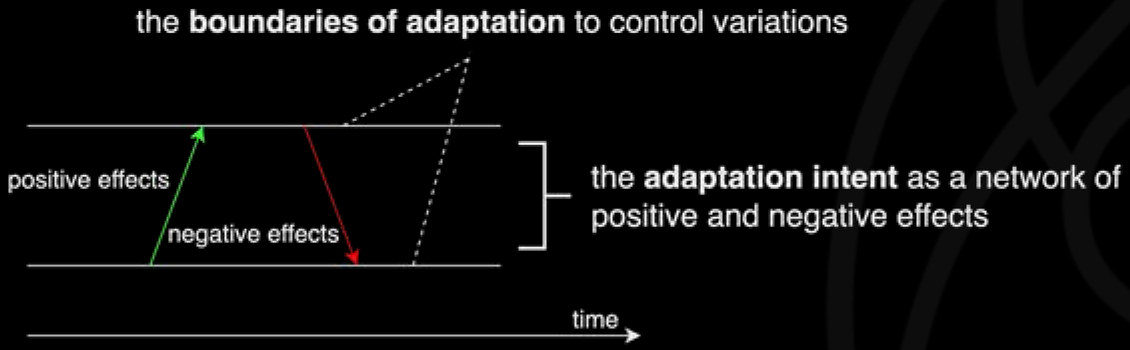


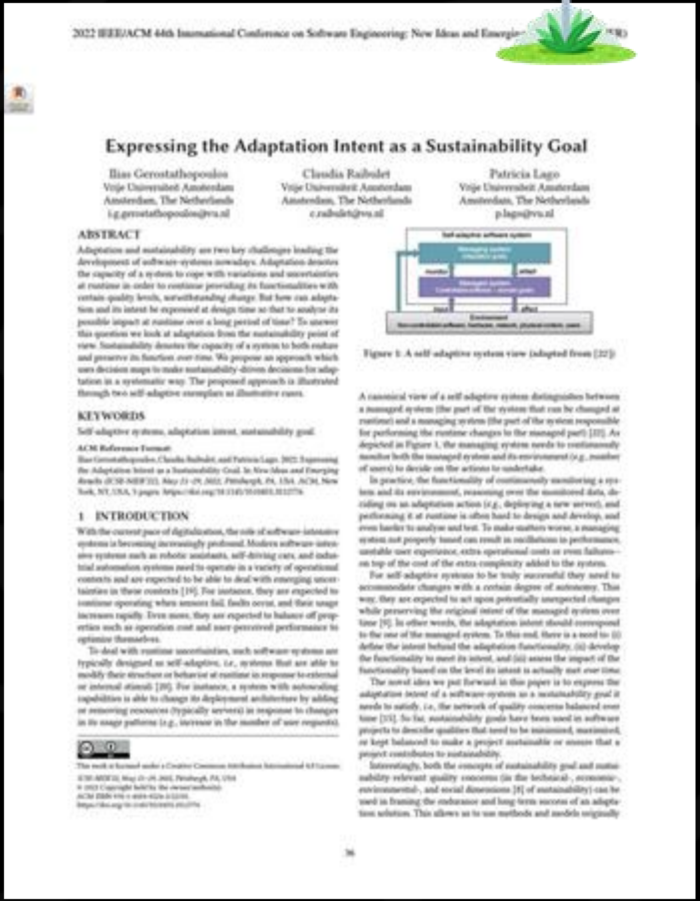
There is no sustainability without **traceability**

P. Lago, N. C. Fernandez, I. Fatima, M. Funke, and I. Malavolta, "The Sustainability Assessment Framework Toolkit: A Decade of Modeling Experience," Softw. Syst. Model., 2024, doi: 10.1007/s10270-024-01230-9. ArXiv https://arxiv.org/abs/2405.01391v2

The (desirable) future: where should we go?

"Balance"




2022 IEEE/ACM 44th International Conference on Software Engineering: New Ideas and Emergin…

Expressing the Adaptation Intent as a Sustainability Goal

Ilias Gerostathopoulos, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands, i.g.gerostathopoulos@vu.nl

Claudia Raibulet, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands, c.raibulet@vu.nl

Patricia Lago, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands, p.lago@vu.nl

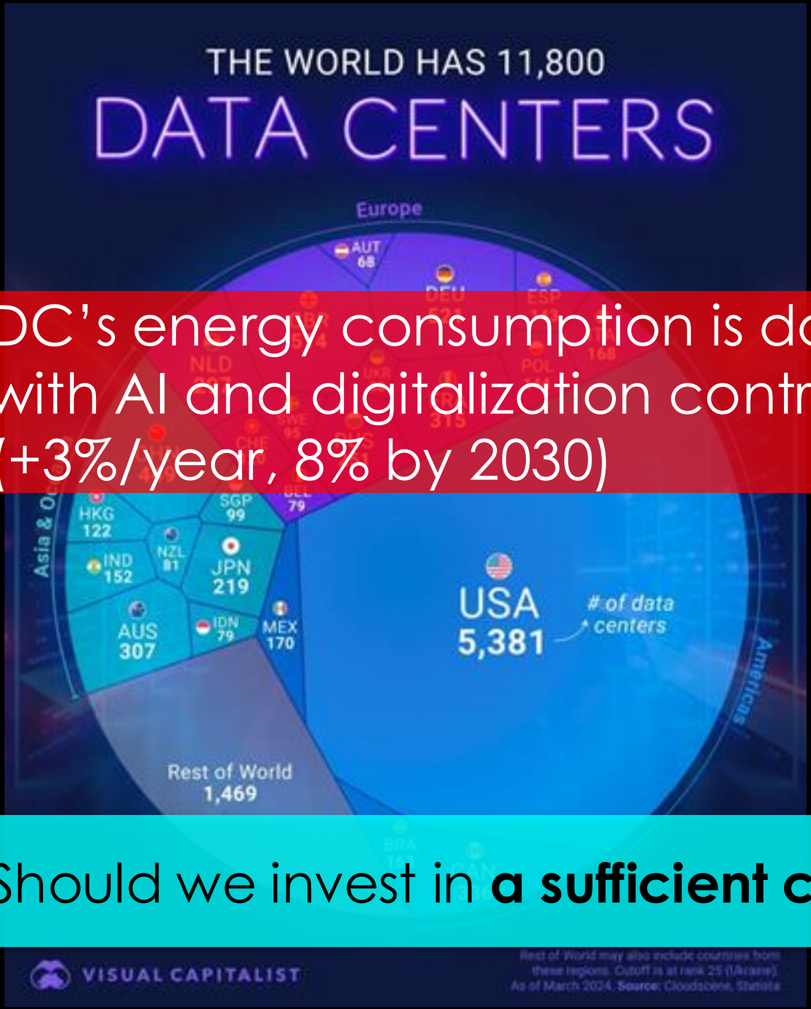
ABSTRACT

KEYWORDS

1 INTRODUCTION

Figure 1: A self-adaptive system view (adapted from [22])

There is no sustainability without **balance**

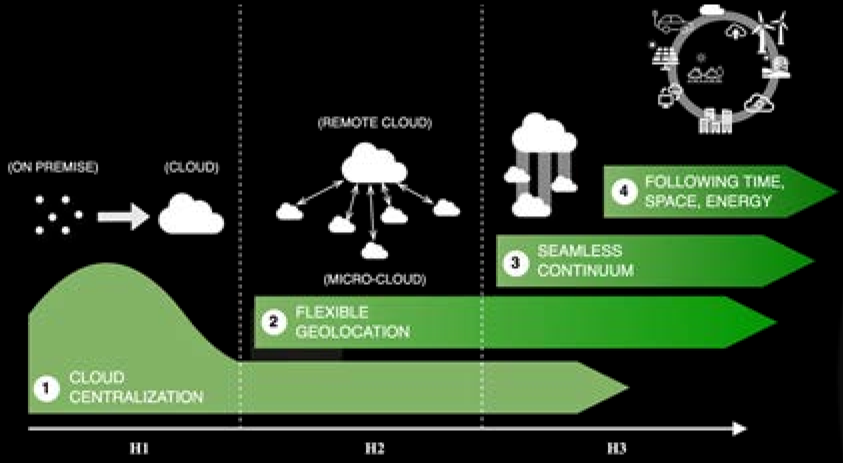


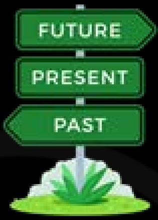
DC’s energy consumption is doubling every 4 years with AI and digitalization contributing to this growth (+3%/year, 8% by 2030)

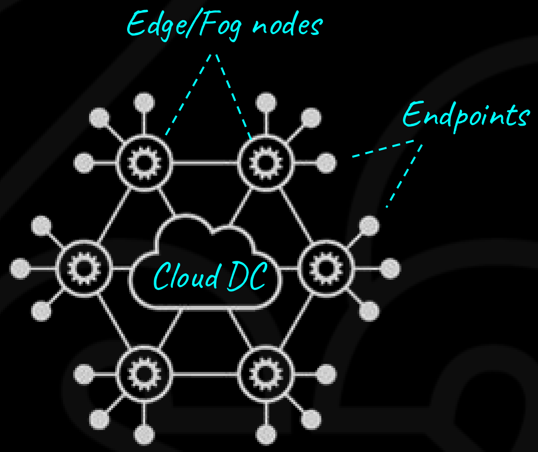
Should we invest in **a sufficient cloud**? How do ***sufficient* SAs** look like?

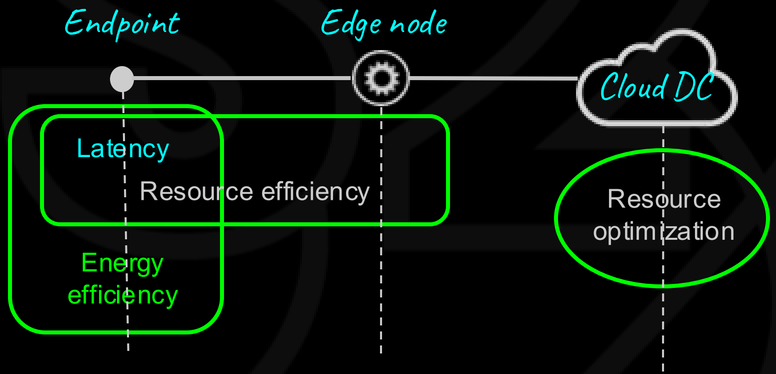
The (desirable) future: where should we go?

The end of cloud as we know it?









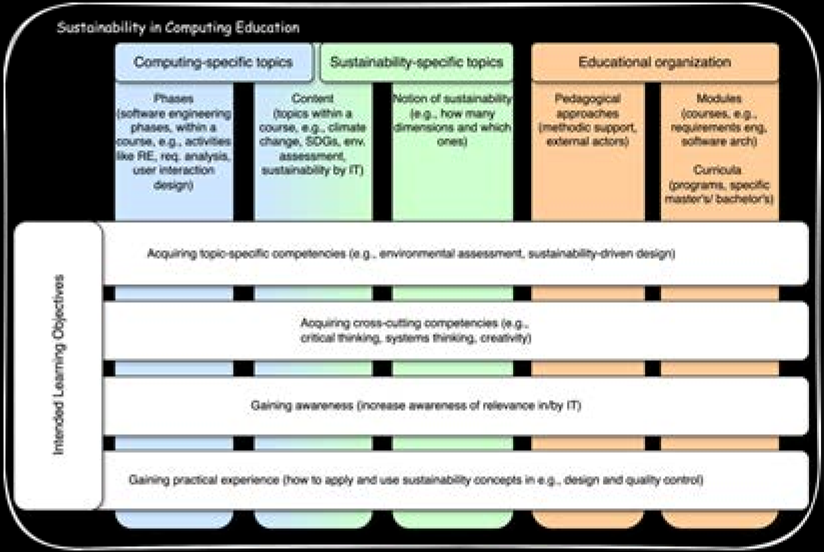
There is no sustainability without **cloud-flexible reference architectures**

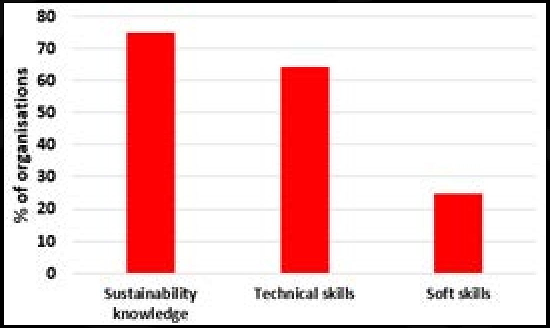
R. Verdecchia, P. Lago, C. de Vries,"The future of sustainable digital infrastructures: A landscape of solutions, adoption factors, impediments, open problems, and scenarios," in Sustainable Computing: Informatics and Systems, Vol. 35(9), 2022, Elsevier.

A. Al-Dulaimy et al., "The computing continuum: From IoT to the cloud," Internet of Things, vol. 27, no. 101272, p. 101272, Oct. 2024.

The (desirable) future: where should we go?

Education and Training

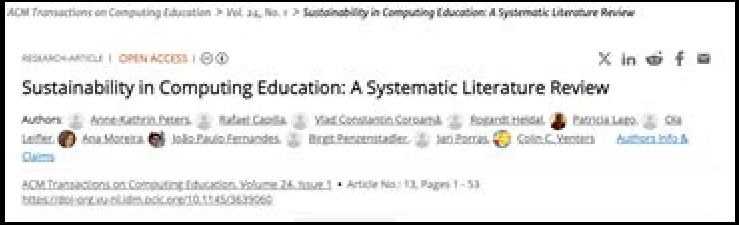




There is no sustainability without **sound skills and competencies**

industry

academia



ACM Transactions on Computing Education > Vol. 24, No. 1 > Sustainability in Computing Education: A Systematic Literature Review

RESEARCH-ARTICLE | OPEN ACCESS

Sustainability in Computing Education: A Systematic Literature Review

Authors: Anne-Kathrin Peters, Rafael Capilla, Vlad Constantin Coroamă, Rogardt Heldal, Patricia Lago, Ola Leifler, Ana Moreira, João Paulo Fernandes, Birgit Penzenstadler, Jari Porras, Colin C. Venters   Authors Info & Claims

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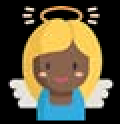
Sustainability competencies and skills in software engineering: An industry perspective

Rogardt Heldal, Ngoc-Thanh Nguyen, Ana Moreira, Patricia Lago, Leticia Duboc, Stefanie Betz, Vlad C. Coroamă, Birgit Penzenstadler, Jari Porras, Rafael Capilla, Ian Brooks, Shola Oyedeji, Colin C. Venters

In summary…

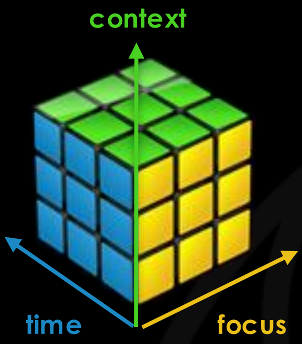


The good

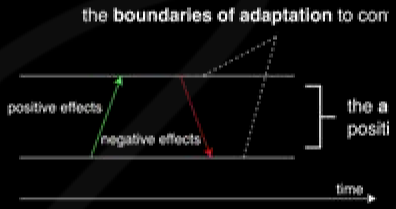
The bad

The mystery

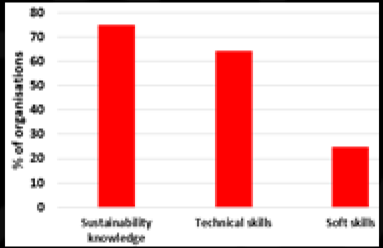
Concepts	DIMENSIONS OF FOCUS	DIMENSIONS OF **TIME** HUMAN FACTORS	ROLE OF **CONTEXT**
SW/SE	TECHNOLOGY	**KNOWLEDGE** SYNTHESIS **MEASURES**	EDUCATION AND **TRAINING**
SA	DESIGN DECISION MAKING	**QUALITY** ASSESSMENT	**SYSTEMIC** DESIGN **TRACEABILITY**



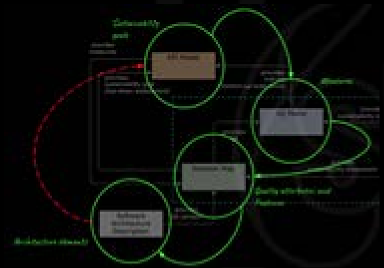
There is no sustainability without **time** and **context**



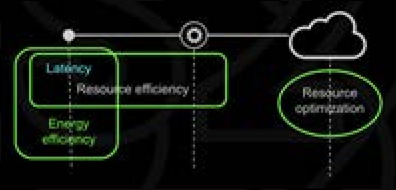
There is no sustainability without **balance**



There is no sustainability without sound **skills and competencies**



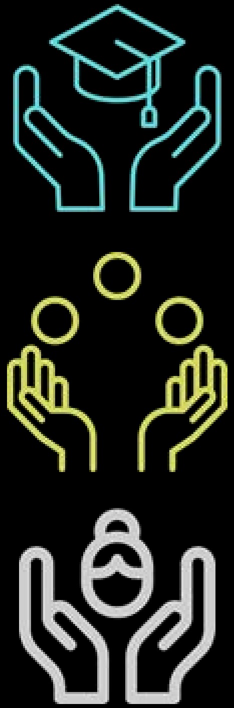
There is no sustainability without **traceability**



There is no sustainability without **cloud-flexible reference architectures**

Thinking of the future…

Def: **Propositions** are statements that accompany PhD dissertations in (some) Dutch universities



Reflections I care to share

1. Multidisciplinary research is hard, interdisciplinary research is *harder*. Sustainability research needs both.
2. Most research questions in software sustainability are old problems that were never solved.
3. Humans drive software engineering: neglecting the first impacts the relevance and quality of the second.
4. We are done with SLRs; what happened to study extensions?
5. "You are what you read." [P. Kruchten, private conversation]
6. "Knowledge has legs and walks home every day" [adapted from Rus and Lindvall (2002), Knowledge management in software engineering. IEEE Software, vol. 19(3)].
7. Think: isn't it ironic to use genAI for presenting a sustainability-related research?
8. Thinking time over publication frenzy.
9. Humans change per extremes: from too little societal impact to too much hype.
10. "Volere è potere" aka "Where there's a will, there's a way." [A. Einstein]

Thank you

Credits: slides, ideas and results are a collective effort with my bright and energetic colleagues in the S2 Group @Vrije Universiteit Amsterdam s2group.cs.vu.nl

Icons: flaticon.com
Images: dreamstime

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