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The Role of Modeling in the Analysis and Design of Sustainable Systems: A Panel Report

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Abstract:

Sustainability should become a key concern in the next generation of engineered systems. While this expectation is relatively straightforward, the question of how to get there is less obvious. The multi-dimensional and intricate nature of sustainability poses challenges in designing sustainable systems and analyzing sustainability properties. Finding trade-offs between economic, environmental, societal, and technological aspects of sustainability is a wicked problem and calls for advanced modeling and simulation methods. In this paper, we report on a panel discussion held at the 28th Working Conference on Exploring Modeling Methods for Systems Analysis and Development (EMMSAD) with four esteemed experts representing four complementary and often conflicting perspectives on the role of modeling for sustainability – stakeholders, digitalization, degrowth and IT, and ethics. We report the key arguments of the panelists, discuss the roles of modeling in the analysis and design of sustainable systems, and finally, elaborate the conflicts among the perspectives, their effects, and potential resolutions.

Keywords: information systems engineering, circular systems engineering, digitalization, digital twins, ethics, degrowth and IT, modeling, model-driven engineering, model-based systems engineering, sustainability, systems engineering.

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1 Introduction

Information systems developed in the 21st century are not only evaluated according to the degree in which they realize functional and traditional non-functional requirements such as performance, flexibility and security. Instead, we see an increasing need for information systems that contribute to sustainability, particularly the development of sustainable systems. We also recognize that sustainability discussions do not stop at the three original sustainability dimensions, *economic*, *environmental*, and *societal,* as introduced by Brundtland (1987), but emerged toward incorporating a fourth dimension, *technical* sustainability (Penzenstadler & Femmer, 2013)[1]. In this latter dimension, information technology (IT)[2] and information systems (IS) are widely considered as key enablers. Firstly, IS and their underlying IT are often considered catalysts for inclusiveness in our ever-increasingly digitalized world, in both a social sense (social sustainability) by providing people access to information and communities, as well as in an economic sense (economic sustainability) by digitally bridging the gap between consumers and producers. Secondly, IS can be used to support the design, optimization, and monitoring of sustainability-related concerns of systems in general (e.g., (circular) supply chains, logistics networks, smart cities, factories) – i.e., information systems for sustainability (IS4S). The panelists also emphasized that sustainable systems can only result from sustainable development methods supported by IS4S.

1.1 A Dualistic Role for Information Systems

Before labeling IS and IT as “silver bullets”, it is important to realize that IS and IT themselves also have a potentially adverse impact on sustainability. Due to its energy consumption, IT is also a massive emitter of CO2, currently contributing to about 2-4% of global CO2 emissions, comparable to the carbon emissions of the avionics sector[3]. When left without intervention, this number is projected to increase to about 14% by 2040 (Belkhir & Elmeligi, 2018). Even more, when looking across the full lifecycle of IT hardware and software, one can see an even broader spectrum of potential adverse impacts on sustainability. Some examples are the exploitation of workers across many hardware and software supply chains (Kirk, 2009; Hope, 2016), and e-waste as a result of improper end-of-life management (World Economic Forum, 2019). As such, there is a need to move toward sustainable information systems (SIS) in terms of the development and operations of IS. Recognizing these contradictory effects and optimizing for a positive outcome is a wicked problem (Rittel & Webber, 1973) for which human experts and decision-makers can benefit from computer-aided support, e.g., in terms of IS4S. As such, we observe a duality between SIS and IS4S. This duality is also exemplified in recent discussions about sustainable engineering methods for digital twins (Fur et al., 2023) – considered here as IS4S – versus digital twins for sustainable systems (Heithoff et al., 2023) – considered here as SIS.

As repeatedly identified by the four panelists, sustainability’s highly stratified and multi-systemic nature (McGuire et al., 2023) obstructs the emergence of SIS and IS4S. A key factor in this is the need to identify, explain, and formally represent the interdependencies between individual sustainability dimensions and to find trade-offs among them efficiently.

The panelists strongly believe that the IS community, especially its conceptual modeling sub-community, can make key contributions to address the above obstacles. Modeling and analysis have been well-researched topics in the IS community; the methods developed in the past can guide systems analysts, designers, testers, and engineers along the development lifecycles. The prevalent mechanism of abstraction (Stachowiak, 1973; Kühne, 2006) that is key to conceptual modeling is well suited to cope with sustainability’s inherent complexity and multi-systemic nature and allows for appropriate and effective formalization of sustainability properties across different disciplines. Within the panel discussions and the remainder of this report, the primary focus was on IS4S while realizing that such methods, techniques, and tools would also need to be fundamentally sustainable. As such, the panel’s focus on “sustainable

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[1] The Karlskrona manifesto (Becker et al., 2015) introduces a fifth sustainability dimension. Individual sustainability refers to the well-being of humans as individuals, and it includes topics such as mental and physical well-being, education, self-respect, skills, and mobility.

[2] We use IT to refer to computing intensive technology in support of information storage, exchange, and processing in general. As such also generalizing from terms such as ICT (Information and Communication Technology) and OT (Operational Technology) as used in more specific contexts.

[3] https://ciandt.com/ca/en-ca/article/climate-crisis-and-technology-sector

systems” implied a focus on the IS4S needed to analyze, design, and monitor systems (in the general sense) from a sustainability perspective while also ensuring that these IS4S are SIS themselves[4].

1.2 Positioning of the Panel

The EMMSAD 2023 panel and this report aim to be a *call to action* for the IS community to steer research toward sustainable analysis and design methods (IS4S), ultimately leading to the emergence of sustainable IS (SIS). Colleagues in the scientific community (Lago et al., 2015; Kristoffersen et al., 2020; Barisic et al. 2023; David and Bork et al., 2023; van der Aalst, et al., 2023), political bodies like the European Commission[5], and international industrial standardization bodies like the International Council on Systems Engineering (INCOSE)[6] have raised similar calls.

In line with the focus of the EMMSAD working conferences on Exploring Modeling Methods for Systems Analysis and Development, the panel took a broad systems engineering perspective. The composition of the panel (see their bio at the end of this paper) ensured the inclusion of a broad spectrum of relevant perspectives and expertise regarding the engineering of sustainable systems. This spectrum included:

1. The awareness that the systems under consideration can not simply be seen as IT systems, but should rather be seen as socio-technical systems in which the former are embedded (Bolte et al., 2022; Sætra, 2021; van Wynsberghe, 2021).
2. The need to involve relevant stakeholder groups and perspectives across the engineering and further development of systems in general (Esteves et al., 2012; Itzik, Reinhartz-Berger et al., 2015), and sustainable systems in particular (España et al., 2019).
3. The use of advanced modeling and simulation techniques enabled by the ongoing digitization and advent of digital twin technologies (Kritzinger et al., 2018; Margaria & Schieweck, 2019), which allow for the analysis and monitoring of sustainability aspects of different systems, as well as support sustainability research (España, Thorsteinsdottir, et al., 2023).
4. The impact that IT (including digital twins) itself may have on sustainability goals across its own lifecycle (Finnveden et al., 2009; Arushanyan et al., 2014; Bellis & Denil, 2022; Lago, 2023; Ramautar, España, et al., 2023; David, Bork, et al., 2023), as well as the needed accounting (España, Ramautar, et al., 2023).
5. The perspective of a potential need for degrowth of the use of IT (España, Hulst, et al., 2023) based on the general socio-economic paradigm that promotes an (equitable) downscaling of production and consumption (Kallis & Schneider, 2008).
6. Empowering the needed reasoning regarding sustainability-related trade-offs with fundamental mechanisms for explanation (Guizzardi & Guarino, 2023), as well as ontologies to enable the semantic grounding of different relevant aspects, including semantic interoperability of data and systems (Guizzardi, 2020), risk and value (Sales et al., 2018), legal relations (Griffo et al., 2021), security (Oliveira et al., 2022), trust (Amaral et al., 2019) and trustworthiness (Amaral et al., 2021), and ethics (Guizzardi et al, 2023; España, van der Maaten, et al., 2023).

1.3 The Panel

To investigate the role of modeling in the analysis and design of sustainable systems, we organized a panel discussion at the 28th Working Conference on Exploring Modeling Methods for Systems Analysis and Development (EMMSAD), co-located with the 35th International Conference on Advanced Information Systems Engineering (CAiSE) in June 2023. The following four complementary perspectives on the role of modeling in the analysis and design of sustainable systems have been presented.

- The *stakeholders* perspective – Iris Reinhartz-Berger (University of Haifa, Israel)

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[4] There is a similar line of discourse in other industrial and scientific communities that are aware of, and sensitive to sustainability, such as the Information and Communication Technology for Sustainability (ICT4S) and the Information and Communication Technology for Development (ICT4D) communities. See the work by Hilty et al. (2015) for definitions and a review of related scientific fields.

[5] https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en

[6] https://www.incose.org/about-systems-engineering/se-vision-2035

- The *digitalization* perspective – Istvan David (McMaster University, Canada)
- The *degrowth and IT* perspective – Sergio España (Utrecht University, the Netherlands, and Universitat Politècnica de València, Spain)
- The *ethics* perspective – Giancarlo Guizzardi (University of Twente, the Netherlands)

The stakeholders perspective articulates what subject matter experts need to be involved in the development of IS4S to be efficient in the modeling, design and analysis of SIS. The digitalization perspective argues that stakeholders of systems (that should become more sustainable) became uniquely empowered by recent advancements in digital technology as models became more than mere paperware abstractions of reality — often, e.g., in digital twins (Wurm, et al., 2023) (when used as IS4S), they are live, real-time representations of complex systems allowing for experimentation with the system, advanced what-if analysis, and real-time automated control for sustainability properties. The degrowth and IT perspective emphasizes the limitations of the digital perspective, identifying the need for sustainable digitalization practices (i.e., SIS), especially scaling back digital infrastructure that seems bloated and redundant nowadays, and argues for better modeling and analysis of the environmental impact of digital technologies; more importantly, this perspective proposes using IT as a leverage to degrow the economy in general. Finally, the ethics perspective positions sustainability as a special case of ethics and sheds light on the need for precise semantics of ethical dimensions, such as beneficence, non-maleficence, autonomy, explicability, and justice across the development of IS4S and SIS.

The panelists provided an opening statement on their perspective and participated in an active discussion loosely based on previously agreed discussion points. In this paper, we report a synthesis of their arguments, discuss identified challenges, and outline actionable research directions ahead. By facilitating a discussion among these often conflicting perspectives, the panel—and consequently this panel report paper—also aims to demonstrate that complex sustainability questions require managing contradicting goals and finding balanced resolutions.

1.4 Structure

The rest of this panel report is organized as follows. In Sections 2–5, the panelists present their perspectives on the role of modeling in the analysis and design of sustainable systems. In Section 6, we discuss the main takeaways that arise from these perspectives and identify key challenges and research directions. Finally, in Section 7, we draw conclusions.

2 Iris Reinhartz-Berger: The Stakeholders Perspective

Key insights

- Systems development recognizes the interdependence of technology and society, emphasizing the need to integrate technical and social aspects for the creation of sustainable systems.
- Stakeholder involvement is crucial in designing sustainable systems, acknowledging the diversity in perspectives and priorities among users, domain experts, developers, regulatory bodies, and industry partners.
- Collaborative and iterative modeling processes play a pivotal role in addressing variations and conflicts in stakeholder requirements, offering tools for visualization, trade-off analysis, scenario analysis, decision support, and iterative design.

Systems development recognizes the intertwined relationship between technology and society, acknowledging that systems are not isolated entities but exist within a broader socio-technical context. By considering both technical and social aspects, system developers strive to create effective, user-friendly, and socially responsible systems that contribute to the intended objectives and meet the needs of stakeholders.

The involvement of the various stakeholders is crucial during the design and analysis of SIS to ensure commitment and engagement. Those stakeholders include *users* and *customers* who can share their needs and preferences; *domain experts* and *professionals* who can provide insights on environmental impacts, sustainable practices, and social considerations; *developers* and *designers* who can suggest potential solutions, after understanding the sustainability goals and constraints; *environmental organizations* and *NGOs* that can offer expertise and guidance on sustainability practices, environmental impact assessment, and conservation strategies; *governmental* and *regulatory bodies* that can provide information on environmental regulations, energy efficiency standards, waste management guidelines, and other relevant policies; and, finally, *industry* and *business partners* that can facilitate the identification of sustainable technologies, materials, and processes.

The requirements and goals of the different stakeholders can vary due to their diverse perspectives, priorities, and interests. They also often exhibit disparities and can occasionally lead to conflicts, reflecting the inherent complexity and nature of the challenges they collectively confront. These variations and conflicts may influence the design and analysis processes in several ways. First, different stakeholders may have varying priorities when it comes to sustainability. For example, environmental organizations may prioritize minimizing environmental impact, while industry partners may focus on economic viability. Second, sustainable systems need to address environmental, social, and economic dimensions. However, stakeholders might have differing degrees of emphasis on each dimension. For instance, government bodies may prioritize regulatory compliance, while users may prioritize user-friendliness. Third, some stakeholders may prioritize short-term benefits, such as immediate cost savings or convenience, while others may emphasize long-term sustainability and resilience. Balancing short-term gains with long-term benefits can be challenging, as immediate actions may conflict with the objectives of long-term sustainability. Fourth, stakeholders from different cultures or communities may have distinct values, social norms, and expectations. Conflicts can arise when these values and norms clash or when there are differing perceptions of what constitutes sustainability. Analyzing and addressing cultural and social considerations is crucial to ensure the design is culturally sensitive, inclusive, and socially responsible. Finally, stakeholder goals may vary based on resource availability, technical feasibility, and the context of the system being designed. Conflicts may arise when stakeholders' goals cannot be met due to resource limitations or technical constraints. Designers must carefully assess and communicate the trade-offs and constraints to manage stakeholder expectations effectively.

To address these variations and conflicts, the design and analysis of SIS must involve collaborative and iterative approaches that promote stakeholder engagement and consensus-building. Some strategies to navigate these challenges include actively involving stakeholders throughout the design and analysis processes, encouraging open dialogue, and information sharing; employing facilitation techniques and mediation processes to navigate conflicts and promote collaboration among stakeholders; utilizing decision analysis techniques that consider multiple criteria and trade-offs to support the decision-making process; maintaining transparency in the decision-making process and ensuring accountability for the design choices made. Other related fields, such as behavioral economics, can be coherently integrated to meet these various challenges (Reinhartz-Berger et al., 2022).

Modeling can play a crucial role in addressing those challenges associated with varying stakeholder requirements and goals including:

1. *Visualization and Communication:* Effective visualization may aid in communicating complex concepts and design ideas to stakeholders with diverse backgrounds and perspectives. It can further help stakeholders better understand the proposed design and its implications, facilitating discussions and alignment.
2. *Trade-off Analysis:* Modeling allows for the exploration and analysis of trade-offs between different sustainability dimensions and stakeholder goals. By quantifying and evaluating the impacts of design choices, models can help identify the trade-offs involved and their implications. This enables stakeholders to make informed decisions and prioritize design alternatives based on their preferences and requirements.
3. *Scenario Analysis:* Models can be used to simulate and analyze different scenarios to understand how variations in design choices and stakeholder priorities impact the system's performance and sustainability outcomes. By simulating multiple scenarios, stakeholders can assess the potential trade-offs, risks, and benefits associated with different design decisions.
4. *Decision Support:* Modeling can serve as a decision support tool by providing a quantitative basis for evaluating design alternatives and their impacts on sustainability objectives. Models can incorporate different criteria and performance metrics, allowing stakeholders to assess and compare various design options objectively. This helps in aligning stakeholder goals and making informed decisions.

5. *Iterative Design and Optimization:* Models support an iterative design process, where design alternatives can be tested and refined based on feedback and stakeholder input. By incorporating feedback into the model and analyzing its implications, designers can iteratively improve the design to better align with stakeholder requirements and sustainability goals.
6. *Collaborative Platform:* Modeling tools can provide a collaborative platform for stakeholders to contribute and interact. Multiple stakeholders can provide inputs, share their expertise, and review the model outputs, fostering collaboration and shared decision-making. This facilitates the integration of diverse stakeholder perspectives and enhances stakeholder engagement throughout the design process.
7. *Documentation and Traceability:* Models serve as documentation of design decisions, assumptions, and their rationale. They provide a traceable record of the design process, enabling stakeholders to revisit and understand the reasoning behind certain choices. This promotes transparency and accountability, and facilitates effective communication among stakeholders.

While existing modeling methods and tools offer bits and pieces for many of these aspects, a holistic and comprehensive approach to model-based design and analysis that potentially considers sustainability concerns as first-class citizens is still missing. Further research and development efforts are needed, including the integration of sustainability dimensions into modeling frameworks, the development of standardized sustainability metrics, the enhancement of stakeholder engagement features, and the creation of interoperable tools that facilitate seamless collaboration and integration of different modeling aspects. Furthermore, interdisciplinary collaboration among researchers, practitioners, and stakeholders from different fields, such as computer science, systems engineering, and social sciences, is crucial to bridge the gaps and develop a more integrated and holistic approach to both IS4S and SIS. These understandings should also be operationalized to action items for higher education institutions, e.g., the need to update their curricula to incorporate sustainability principles and practices in software and systems engineering, develop collaborative programs and courses that bring together multidisciplinary stakeholders that can contribute to a holistic understanding of sustainability and the interconnectedness of systems, and provide hands-on experience and experiential learning opportunities.

3 Istvan David: The Digitalization Perspective — the Good, the Bad, and the Ugly

Key insights

- Digitalization created new opportunities in leveraging modeling for sustainable systems engineering – such as digital twins and AI.
- We must be cognizant of the sustainability limitations of digital technology – such as the technical sustainability of digital twins and the environmental sustainability of AI.
- Bipartite view on sustainability: sustainable systems require sustainable methods – modeling helps in both.

Current systems engineering practices fall short of accommodating sustainability criteria that are highly complex and often measurable only in the long run. Experts are calling to action in developing novel methods and tools to support the engineering of sustainable systems (van der Aalst et al., 2023; Kristoffersen et al., 2020). Surely, we must take our systems engineering practices to the next level to effectively handle the complexity of the next generation of systems that are fully expected to be sustainable in the environmental, societal, economic, and technological sense (Lago et al., 2015).

Modeling, and especially model-based and model-driven engineering techniques are powerful tools in taming complexity. As such, modeling is a particularly important enabler in addressing the challenges associated with sustainability. Unfortunately, traditional modeling techniques do not scale well enough to effectively support wicked problems such as the engineering of sustainable systems (Barisic et al., 2023). Digital transformation efforts and specifically, the surging adoption of digital twins (Kritzinger et al., 2018) and the digital thread (Margaria and Schieweck, 2019) have opened new frontiers in making use of modeling. To fully leverage these opportunities (the Good), we must understand the limitations (the Bad) of modeling and simulation-based digital techniques, and we must embrace the grand challenge (the Ugly) that systems will become sustainable (SIS) only if their engineering and operation practices are sustainable (IS4S) in the first place.

3.1 The Good: Digitalization created unprecedented opportunities

Organizations are becoming more digitized than ever before. An important result of this trend is the widespread adoption of digital twin based engineering methods.

Digital twins improve on traditional modeling capabilities by putting models into action, defining a real-time proxy representation of physical systems, and capturing their prevalent state. Moreover, digital twins are equipped with control capabilities over the physical system, further expanding the impact of having explicit, continuously maintained models of the system that allow for enhanced reasoning capabilities as to how to control the physical system for optimal behavior. These traits enable an array of beneficial capabilities in support of developing SIS, and position digital twins as key factors for organizations to realize their sustainability goals.

At the design phase of SIS, for example, digital twins can provide a virtual surrogate of the physical system and enable experimentation in a virtual space (Madni et al., 2019). Virtual experimentation offers faster, safer, and more cost-effective ways for evaluating complex design alternatives thanks to high-fidelity models of the real system, enabled by real-time data collection and processing from the real system. Rapid experimentation supported by design-space exploration becomes a viable alternative to physical prototyping, further improving the potential of finding optimal trade-offs between functional, extra-functional, and sustainability properties.

During operation, digital twins can be used for better control over sustainability goals (Daoutidis et al., 2016). Some pertinent examples include optimized energy consumption, reduced waste, and improved productivity. These benefits, again, are due to the high-fidelity models at the core of the digital twin that are continuously updated by a real-time stream of data from the physical system. The digital twin's ability for real-time analysis, optimization, and control allows for deferring design decisions with uncertainty to the operational phase and controlling the underlying asset based on data that becomes available only later.

Finally, digital twins extend the use of models into the post-life of systems, i.e., the period after the useful operation time. Value retention (Reike et al., 2018) is a key mechanism that fosters sustainability. Digital twins allow for retaining value from models through the data they accumulate during the lifetime of the system. The data corresponds to the model, representing specific instances and snapshots of the system that can be analyzed and reused in new incarnations of the same system or in the design of completely new systems.

The digital thread is an end-to-end digitized stream that starts at the conceptualization of a system and spans through its entire lifecycle, creating a loop between digital and physical entities. Conceptually, the digital thread is a process-oriented framework within which digital twins operate. By modeling the underlying process explicitly, the digital thread allows for further degrees of freedom in finding sustainability trade-offs. For example, a less sustainable design decision might be considered acceptable if it realizes more value during operation or the post-life of the system.

Advanced digitalization has now made its way into business and industry as an increasing number of organizations realize its value in supporting their sustainability ambitions. Capgemini reports that 60% of organizations believe digital twin technology is critical to improving sustainability efforts[7]. Some of the sectors with visible benefits include manufacturing, where multi-million dollar savings are being regularly reported thanks to digital twinning[8]; smart cities, where Accenture estimates energy consumption rationalization by 30-80% through digital technologies[9]; and traditionally lower-digitized sectors, such as biophysical systems and agriculture, where digitalization improves crop-to-energy ratio and substantially stabilizes the supply chain (David, Archambault, et al., 2023).

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[7] https://www.capgemini.com/us-en/news/press-releases/digital-twins-are-a-catalyst-to-fulfilling-organizations-sustainability-agenda/

[8] https://partners.wsj.com/samsung/technology-speed-of-change/unilever-uses-virtual-factories-to-tune-up-its-supply-chain/

[9] https://www.accenture.com/_acnmedia/PDF-147/Accenture-Virtual-Twin-and-Sustainability.pdf

3.2 The Bad: Digitalization is no silver bullet

Despite its tremendous added benefits to modeling, digitalization is no silver bullet, and its limitations require the attention of researchers, adopters, and policy-makers alike.

The development of models for digital twins is substantially hindered by the complexity and vagueness of sustainability goals. For example, of the 17 SDGs formulated by the UN, 14 directly incorporate socio-economic elements (goals 1–12, 16, and 17) rendering their modeling and analysis a complex problem that directly affects digital twinning technology (Tzachor et al., 2022) — a similar controversial discussion was stressed in a recent survey on how AI is used for sustainability (Schoormann, et al., 2023). A deeper, ontologically-founded understanding of sustainability is needed to bridge the gap between high-level SDGs and actionable engineering activities.

Maintenance is another important challenge that might render digital twins useless in supporting sustainability ambitions. As the physical system changes, the digital twin must change with it to ensure that the analysis of sustainability properties remains sound. This requires system evolution and adaptation mechanisms which are currently in the early stages of research (Wright et al., 2022). In addition, complex problems require subject-matter-specific digital twins to be composed into systems of twins, necessitating discovery and interoperability capabilities that currently exist only at conceptual levels.

Organizational challenges might also plague the effectiveness of digital twins. Lower-digitized domains often lack the expertise required to make use of advanced digital technology. Data management and enterprise IT architecture are some of the pertinent examples of such often lacking expertise. The lack of expertise, in turn, leads to a lack of understanding and trust in the digital twin. As a consequence, autonomy of digital twins is hard to achieve, especially amid safety and security concerns. Explainability of the digital twin's reasoning is paramount in improving stakeholder trust and accelerating convergence to higher autonomy.

We must acknowledge the limitations of digital technologies and remain firmly with two feet on the ground when estimating their capabilities in fostering sustainability.

3.3 The Ugly: To become sustainable—we must become sustainable

Here's the ugly truth that often gets overlooked in discussions about sustainable systems: in order to engineer sustainable systems (SIS), our engineering methods must become sustainable as well (IS4S). Instead of shifting the problem of sustainability and hiding it into unsustainable engineering methods, we must effectively address it. Lago (2023) warns that despite the promises of digitalization, current digital practices are not sustainable, and in the end, "*an unsustainable digital society is prone to fail*". Indeed, while the importance of digital twins in sustainability is clear, it is important to acknowledge that digital twins themselves need to be sustainable to support larger sustainability goals. Bellis and Denil (2022) report four important sustainability challenges of digital twinning: *energy consumption*, *modeling effort and complexity*, the *ability to evolve* with the physical twin, and the *deployment of the twin architecture* within organizations. Predictive methods and improved design automation are key to alleviating these issues. Fur et al. (2023) offer solution patterns for these problems, such as process-aware digital twins with the ability to reconfigure themselves based on contextual information.

Further improvements can be realized by finding trade-offs across lifecycles of systems and digital twins. This idea has been recently proposed as *Circular Systems Engineering* (David, Bork, et al., 2023), in which process-aware digital twins are situated in properly modeled and controlled digital threads, allowing for elevated contextual information for the digital twin, reasoning about the post-life of systems, and retaining value over numerous system life-cycles.

From the point of view of technical sustainability, chiefly associated with the prolonged usage of the system, digital twin evolution and supporting frameworks (David & Bork, 2023) will become important enablers. From an economic sustainability point of view, automation of digital twin engineering by machine learning (David & Syriani, 2023) carries high potential. As complex systems ought to have complex models and simulators, automating the design of digital twins that rely on these services will go a long way.

At a larger societal level, the staggering differences between economies lead to digital divides (Tzachor et al., 2022) that prevent lower-income economies from embarking on advanced digitalization journeys. Therefore, a digital solution that worked in fostering sustainability in one context (e.g., a smart city solution in a well-endowed city), might not be available in another context. Inclusive partnerships are key in fostering societally sustainable digital twinning. That is, our engineering processes must include those who may be affected by the digital twins that govern socio-technical systems.

3.4 By way of conclusion

Digital transformation efforts have opened new frontiers in making use of the vast body of knowledge in modeling to support the development of sustainable systems. There is a consensus that the next generation of systems must become more sustainable. To get there, we must leverage the opportunities digitalization provides. However, we must understand its limitations, and must not forget that our engineering practices must become more sustainable as well. While maintaining a technological focus in IS engineering is a must, we shall also remember the importance of social and ethical responsibility. We must understand how our systems affect specific strata of global society, and we must actively seek ways to include people in the design and operation of our systems who may be affected by the decisions based on simulation models.

Promoting sustainability in systems engineering practices is our joint responsibility. We must acknowledge that humankind faces immense challenges that seem to be insurmountable within the current governing frame of thinking. We need to revise our current ways of coexisting with our environment and with each other. Elevating sustainability to a leading principle in systems engineering, while it might seem a minuscule improvement in the grand scheme of things, will go a long way as it will render the next generation of our systems more environmentally friendly and more useful for society at large.

4 Sergio España: The Degrowth and IT Perspective

Key insights

- Modeling methods enable analyzing the often neglected trade-offs among sustainability concerns when developing IT-based solutions, especially when they incorporate ethical reasoning techniques.
- There is a prevalent techno-optimistic stance on the potential of IT to tackle sustainability challenges, and modeling should help us become humbler.
- We need to consider the appalling evidence that the economy in general, and also IT in particular, need to degrow if we are to walk true pathways to sustainability.

Due to the rising awareness of the many social and environmental challenges that humanity is facing, there is an increasing interest within the IT academic field on how IT can contribute to sustainability. And yet, both in industry and academia, we can still observe that IT researchers, analysts, and designers tend to overlook or ignore the trade-offs among sustainability concerns caused by the methods and software they create. It is often the case that they just focus on one or two sustainability impacts that conveniently highlight the benefits of their contributions. When this is taken to the extreme, it promotes a naïve techno-optimistic attitude that in the best case distracts from finding strong sustainability solutions, and in the worst case, it aggravates the problems due to the negative externalities of the IT interventions. See Appendix A for a summary of weak and strong sustainability viewpoints. Furthermore, sustainability is a multi-dimensional construct, and, as research in the area of IS4S has progressed, we have gradually increased the number of dimensions, as explained in the introduction. As a result, my position is that modeling methods should help IT analysts and designers become more aware of the many trade-offs among sustainability concerns and be more techno-realist.

To illustrate the importance of the trade-offs in IT design and analysis, think of the well-known tension between software security and usability. It has been extensively investigated how increasing one might decrease the other, and it has become a common example of the trade-offs among software qualities or non-functional requirements. The same happens among sustainability concerns, as exemplified in the following example, adapted from Lago (2016). In Northern European countries where winter nights are long and dark, smart urban lighting systems become important to promote that children play outdoors. Such an intervention might increase their mood, improve their sleep patterns, and eventually improve their health. However, street lighting is one of the most important factors of energy consumption in cities, having a significant contribution to their CO2 footprint (Ożadowicz, 2017). In megacities with heavy traffic and surrounding industry, municipalities often deploy pollution monitoring systems that analyze the composition of the air, taking regular measurements that inform the decisions of policy-makers who aim at improving air quality (Yi et al. 2015). Such IT interventions inevitably resort to sensors and other hardware which produces many negative impacts across their lifecycle, such as depletion of natural resources, inhumane living conditions in mines, CO2 emissions due to transportation and manufacturing, and unhealthy working conditions in factories; see, for instance, a review on IT impacts across the lifecycle by Arushanyan et al. (2014). Furthermore, many IT interventions increase our dependency on technology, making societies vulnerable to the impact of IT failures. When analyzed thoroughly and deeply enough, many concerns belonging to different sustainability dimensions surface, and their relationships become complex. A causal loop diagram (Kim, 1992) or an architecture decision map (Lago, 2019) will reveal the cause-effect relationships, and loops with reinforcing or balancing effects. And, when we consider the temporal dimension, we might even find rebound effects. Before giving the go-ahead to an IT implementation of such nature, it is critical to discover its potential impacts and analyze its trade-offs.

Modeling the cause-effect relationships and trade-offs facilitates engaging the stakeholders. The sustainability impacts and trade-off models should then inform IT engineering. During IT analysis and design, many methods exist that could facilitate identifying ethical conflicts and dilemmas, trace the positive and negative effects to (fragments of) IT conceptual models, and discuss the problems and potential solutions with stakeholders. We can refer to them as ethical reasoning methods for IT (España & van der Maaten et al. 2023). When identifying the impacts of IT in society and the environment, it becomes more informative to information systems analysts and software engineers if the effects are traced to conceptual models; either to the whole model, or a fragment of it, or a specific element. It will be interesting to investigate how to do this with different types of IT artifacts, ranging from visions or scenarios of the IT (Arushanyan, Ekener-Petersen, et al., 2015), to models of the data (Do Nascimento Fidalgo, De Souza, et al., 2012), software architecture (Jagroep, van der Werf, et al., 2017), etc.

However, it is important to not just conceptualize the impacts but to also estimate (first) and measure them (later), since it is the way to ascertain that the IT has the expected sustainability impacts. There are many impact measurement methods available, which we can group into families such as lifecycle assessment (Finnveden et al., 2009), social impact assessment (Esteves et al., 2012), and environmental, social, and governance accounting (España, Bik, et al., 2019; España, Ramautar, et al., 2023). Among such methods, IT analysts and designers will need to select the ones that are most applicable to the IT project, product, or service situation. They all have in common that they prescribe, suggest, or facilitate the definition and operationalization of sustainability performance indicators that allow estimating or measuring the effects of some phenomenon or artifact (in our case, IT interventions). The results of the impact measurement endeavors, whether punctual or based on continuous monitoring, can validate the IT design and analysis decisions or inform the reengineering of the systems by establishing an improvement cycle.

With respect to my discontent with the prevalent techno-optimism, we need to move the discussion up to the macro level. Because I believe that there lies the root cause of all sustainability problems. Why are we experiencing human-induced global warming? Why are we incapable of redistributing wealth equitably? In short, why can't we achieve the sustainable development goals? Well, many experts think it is due to an inherent flaw in the prevailing economic system: the growth imperative. If a company or a country stops growing, it goes bankrupt. And economic growth goes hand in hand with an exponentially increasing exploitation of nature, and also with the unjust distribution of the benefits and burdens of this growth (España & Hulst et al., 2023). The current global rate of production and consumption is socially and environmentally unsustainable. Unfortunately for our scientific community, IT sustains the apparatus of the growth-oriented economic system (Veit & Thatcher, 2023). So I do agree that energy consumption has an important impact on the IT's lifecycle, but I argue that this is not the core problem. Because even if we achieve breakthroughs in energy efficiency or decouple growth from energy consumption, the rebound effects or Jevons' paradox will likely negate the effect of the efficiency gains (Santarius et al., 2020). And I also agree that a fast-paced technology push is placing IT in the market without proper regard for its social externalities, but again this is just a symptom of an economy disconnected from social needs. Even if policy-makers define technical or legal frameworks to take countermeasures against algorithmic bias in AI, against the gentrification problems caused by Airbnb and the likes, or against disinformation in social media, they will always be several steps behind. Because the root cause of most, if not all social and environmental sustainability problems is the growth imperative and the values of the capitalist system.

It is understandable that, within our scientific communities, we like to think of IT as a key ingredient in sustainability-oriented interventions. We also like to think that we can contribute to sustainability pathways from our industrial sector and scientific discipline; it can give purpose to our academic careers. It is even tempting to adopt a techno-optimist, green growth stance. By techno-optimism, we refer to “the belief that science and technology will be able to solve the major social and environmental problems of our times, without fundamentally rethinking the structure or goals of our growth-based economies or the nature of Western-style, affluent lifestyles” (Alexander & Rutherford, 2019). Green growth (wrongly) assumes that the efficiency gains brought by so-called ‘green’ technological change and substitution will enable the decoupling of the growth of gross domestic product from resource use and carbon emissions (Hickel & Kallis, 2020). I understand that consultancies and industry think-tanks sing praises of green growth. Given that expressing post-growth ideas is political suicide, mainstream political parties are also more prone to green growth-oriented discourses. However, scientists and IT practitioners committed to sustainability require a transformation mindset (Mann et al., 2018) and should be aware of what the latest reports of the Intergovernmental Panel on Climate Change have stated about this (IPCC, 2022). All evidence points to the fact that green growth is a cornucopian chimera (Parrique et al., 2019), the only pathway to sustainability is degrowth. Degrowth is a socio-economic paradigm that promotes an equitable downscaling of production and consumption (especially in the Global North), focusing on increasing human well-being while simultaneously enhancing short- and long-term ecological conditions at both local and global levels (Kallis & Schneider, 2008). While the relationship between degrowth and IT is yet a matter of debate, aiming at post-growth pathways would have two major consequences for our discipline (España & Hulst et al., 2023):

- We should consider the **degrowth of IT**; that is, reducing the production and consumption of IT, paying attention to IT’s lifecycle, and enabling impacts. For instance, reducing the energy consumption of data centers, engineering software, and hardware that lasts longer.
- We should consider **degrowth by IT**; that is, using IT to apply degrowth principles in other domains or industry sectors, paying special attention to enabling and structural macro-level impacts. For instance, using IT to map resource demands and provisions in circular economy ecosystems, using IT to elicit transformational change towards sustainable and equitable degrowth.

These degrowth and IT ideas are also encompassed by the notion of digital sufficiency (Santarius et al., 2022), which suggests several dimensions along with strategies and policy proposals to realize the idea. The notion of degrowth is also implicit in the call for a digital reset (Lange et al., 2022), which strongly advocates for a fundamental redirection of the purpose of digital technologies for a deep sustainability transformation and proposes policy strategies for sustainable digitalization.

Consequently, a relevant role of modeling in the design and analysis of sustainable IT is:

- Making IT analysts, designers, and other stakeholders more aware of the many systemic levels at which IT has positive and negative sustainability impacts.
- Facilitating the analysis of the complex trade-offs among sustainability concerns that IT interventions typically have.
- Provide a sustainability improvement loop from system use back to the design and analysis processes via impact measurement.
- Produce a humbling effect on IT analysts and designers, so they become less techno-optimistic.

In sum, modeling methods should help us elicit, represent, and reason about the many systemic effects of IT, and aid in effectively using IT as an ingredient in the interventions to make humanity’s behavior more sustainable.

5 Giancarlo Guizzardi: The Ethics Perspective

Key insights

- The design of sustainable systems requires the formulation of determinate goal-oriented requirements for these systems. These requirements (i.e., sustainability requirements) are a special case of ethicality requirements.
- Ethicality Requirements have their focus not on technological solutions but on the cyber-social systems in which technology is embedded. Ultimately, this is then a problem of designing cyber-social systems for normative compliance but with a focus on ethical norms.
- To bridge abstract ethical norms and the practice of systems design, we need to precisely and explicitly articulate the semantics of the ethical dimensions on which these sustainability requirements are formulated. We also need to do that for the semantics of the data that needs to be shared, reused, and interoperated (in line with the FAIR principles) for managing these cyber-social sustainable systems.
- Semantically clarifying and grounding all these notions depend on properly conducting their ontological analysis.

The gist of the position I would like to put forth here is the following: sustainability, in the sense of UN's Sustainable Development Goals (henceforth, SDGs) (United Nations, 2023) is about the definition of goal-oriented requirements for the design of systems (in the broad sense of the term). Moreover, sustainability requirements are a special case of ethicality requirements. I elaborate on these two points in the sequel.

Firstly, let me elaborate on the notion of ethicality I am putting forth here. Drawing from (Guizzardi et al., 2023) and (Sales et al., 2018b), ethical reasoning can be elaborated: (1) using the notions of value (and anti-value), and (2) assuming the ethicality requirements are ecological requirements.

Let me start with issue (1). *Value* (in a nutshell) can be thought of as the degree to which a *value experience* enabled by a *value object* (given its intrinsic *capacities*) in combination with certain aspects of an *agent* and of its environment satisfy that agent's *goals* (the agent being the *value subject* in this case). *Risk* can be considered as a dual notion of Value. Not only because only things that are of value can be at risk, but because in a sense risk is structurally very similar to value but with reverse polarity, namely: risk (in a nutshell) can be conceived as the degree to which a *risk experience* enabled by a *risk object* (given its intrinsic *vulnerabilities*) in combination with certain aspects of a *threat entity* (e.g., its capacity and *intention* – in case the threat entity is an agent) and of its environment can dent that agent's goals (the agent being the *risk subject* in this case). If we take the risk to be anti-value or negative value, we can just speak of a general notion of *Value Assessment* considering both positive and negative values when assessing the relation of entities and the experiences they enact, and their impact on the goals of an agent.

As discussed at length in (Guizzardi et al., 2023), before we can employ specific ethical strategies and methods for (value) conflict resolution, we need to be able to: precisely articulate the semantics of ethical dimensions (e.g., beneficence, non-maleficence, autonomy, explicability, justice), as well as of the domain-concepts that will be referred to when instantiating these ethical dimensions; use these to operationalize an implementation strategy bridging abstract ethical norms and the practice of systems design.

By employing the notions elaborated above, we can think of beneficence as acting in a way that contributes to value (contributes to producing positive value assessments), and non-maleficence, as not posing risk (not contributing to producing negative value assessments). Moreover, as shown in (Guizzardi et al., 2023), based on these notions, one can build a notion of (rational) *preference* (i.e., a rational agent prefers A over B if she has a greater positive value assessment of A compared to B), which is used to elucidate *decision-making* (e.g., decisions are intentions that result from *deliberations* grounded on preference), which in turn can offer a notion of explicability based on reconstructing actions back to decisions, back to preference, back to value assessments and goals. Furthermore, autonomy is conceived in terms of the delegation of goals from the value subject to the system at hand by explicitly bestowing this system with rights, duties, powers, permissions, no-rights, subjections, immunities, and disabilities. Finally, justice is an immense topic on its own. However, as the first approximation here, we can think of a notion of fairness (which is not addressed in (Guizzardi et al., 2023)) as “treating equally entities that are value-equivalent”. In other words, a procedure is fair if it ascribes the same burdens and benefits to two entities A and B that are equivalent under value assessment.

Now let me go back to issue (2). In which sense are ethicality requirements ecological requirements? In the sense that the stakeholders of a designed system are not just the users of the system but all agents in that ecosystem whose goals are impacted by experiences enacted by the system. That is why the value/risk subject in the case of ethical systems is necessarily a collective agent that includes as members representatives of these impacted stakeholders (a principle observed, for example, in the CARE principles (GIDA, 2020)). For this same reason, the designed system we have been discussing here cannot be just a computational system, but it must include the cyber-social system in which the former is embedded. This position is in line with (Bolte et al., 2022; Sætra, 2021; van Wynsberghe, 2021).

What we just did is a brief exercise in ontological analysis. I claim that this type of ontological analysis can greatly benefit the analysis of sustainability requirements such as the SDGs, as well as the formulation and operationalization of requirements for socio-technical systems that must be conformant to explicitly defined (collective) goals. The latter task is ultimately a task of concretely implementing systems for normative compliance in the sense of (Ingolfo, 2015), but now focusing on ethical (in particular, sustainability) norms. We will certainly need to complement the analysis of the aforementioned notions with other fundamental notions such as, to begin with, the very notions of system and of sustainability, but also notions such as reliability, resilience, and safety (all these notions appear in many of the SDG’s indicators). This approach, however, also gives us a methodological path for such a pursuit. In any case, as first approximations, we can take sustainability to refer to the capacity (hence, a disposition) of a (cyber-social, socio-technical) system to preserve collective goals (by preserving essential properties of the system itself) in a reliable and resilient manner, i.e., in a way that is repeatable and predictable, by resisting adverse forces and adapting to changes in its environment.

In a direct manner, the previous analysis gives us a vocabulary and conceptual framework to analyze these types of requirements, besides informing us of what kinds of concepts and constructs we need to have contemplated in our requirements engineering and system design languages (i.e., IS4S). These include goals, value, risk, capacities, vulnerabilities, situations, intentions, processes and events, legal relations (e.g., contracts, agreements), as well as several relations that can be established between these notions (e.g., goals can be decomposed into subgoals, can influence each other, events can bring about situations, situations can satisfy goals, events can be manifestations of capabilities). It also gives us a landscape to look at the myriad of existing modeling languages, tools, and methodologies that have been developed and matured over the years in disciplines like computer science, information systems, and system science and engineering, as well as a blueprint for integrating them. Finally, a fuller analysis of sustainability and related notions (e.g., reliability, resilience, safety) should lead to the systematic (re)design of modeling to properly capture these notions – in line with what has been successfully carried for notions such as value and risk (Sales et al., 2018b), security (Oliveira et al., 2022), trust (Amaral et al., 2020), and legal relations (Griffo et al., 2021). However, as a complementary take, we focus on the fact that these notions are grounded, justified, and elaborated in terms of an ontological analysis of ethical dimensions.

This kind of ontological analysis is also crucial for the conceptual clarification and semantic disambiguation of domain-related notions (e.g., water-waste safe treatment, water stress, water-use efficiency, decent job, productive employment, and many others). This work, in turn, allows for defining standard vocabularies and conceptual reference models for domain notions in terms of core and domain ontologies (Falbo et al., 2013). This is also an important contribution to enabling the interoperability and reusability of data (according to the FAIR data management principles (Jacobson et al., 2020)). Once more, sustainability requirements and, generally, ethicality requirements must be formulated considering the goals of collective agents. However, to satisfy these requirements, we will need to promote effective collaboration within these collective agents and among collective agents. That cannot systematically happen without sharing goals and data, and, without the capacity to safely align different worldviews.

Asking for conceptual clarification and a deeper ontological/semantic analysis of these notions can seem at first to be a hair-splitting intellectual exercise in face of the urgency associated with the topic of sustainability. However, without these activities, we run the serious risk of not being able to bridge the abstract formulations of requirements and norms and the engineering of concrete socio-technical systems. Moreover, without such effort, we may not be able to establish determinate criteria for assessing whether these ethicality requirements are satisfied by these systems or not.

6 Discussion

In the following, we will discuss the findings and key takeaways from the panel discussion. First, we have a look at the key roles of modeling identified by the different perspectives (Section 6.1), and then, we elaborate on the challenges of integrating all these roles toward fostering sustainability (Section 6.2).

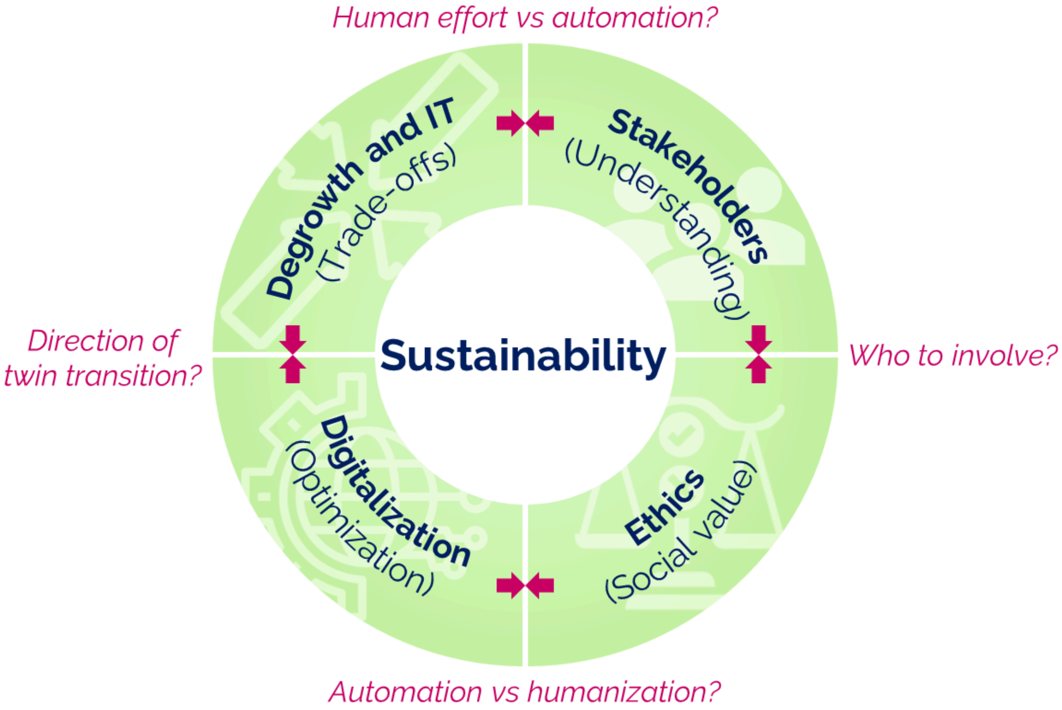

Fig 1. The four perspectives (in bold font) with their dominant roles of modeling (in brackets below the perspective), and conflicting points between them (as questions at the border of the circle).

6.1 The Various Roles of Modeling

The central question of this panel was the *role* of modeling in the design and analysis of sustainable systems. The four perspectives identified four key roles of modeling as follows: i) *Understanding* the highly multi-systemic and stratified nature of sustainability (the Stakeholders perspective); ii) *Improving* systems, including optimizing, verifying, enacting, and monitoring sustainability properties (the Digitalization perspective); iii) *Finding trade-offs* among sustainability dimensions (the Degrowth and IT perspective); and iv) *Formalizing ethics* and other social constructs, such as juridical principles and fairness rules as properties that can be analyzed (the Ethics perspective). Notably, modeling can play many other roles for the design and analysis of sustainable systems–however, this panel report focuses on the roles of models which were stressed by the perspectives of the panelists and supported by the discussion with the audience.

The first role, *understanding* of sustainability properties, can be driven by involving more diverse viewpoints in the modeling process. It is essential to involve all *relevant* stakeholders in modeling, and not involve those with weaker notions or ignorance (Penzenstadler, Femmer & Richardson, 2013). Participatory modeling (Stave, 2010) has been recognized as a way to incorporate diverse groups of stakeholders around sustainability questions and their analysis. Participatory modeling also acts as a learning process that can externalize not only the explicit but also the implicit knowledge of stakeholders

(Voinov et al., 2018). Further strides toward effective modeling and analysis can be made through more systematic modeling methods, such as collaborative modeling (David et al. 2021, Franzagho et al., 2018) and multi-paradigm modeling (Mosterman & Vangheluwe, 2004), which foster formal yet productive modeling environments, accounting for domain-specific vocabularies different stakeholders might possess. Moreover, conceptual models, as defined by Mylopoulos (1992) — i.e., models created and consumed by humans for means of common understanding and meaning negotiation — need to be combined with models and techniques of engineering disciplines like differential equations and system dynamics simulations to account for the stratified and multi-systemic nature of sustainability, and, at the same time, enable all involved stakeholders to engage in conceptual modeling. As a consequence of this active engagement, modeling can realize the role of establishing and communicating a mutual *understanding*.

The second role, *improving systems*, becomes attainable after the first role has been filled, i.e., once a proper understanding of sustainability properties has been established. Reasoning about the optimality of sustainability properties is particularly important to be supported by rigorous formal models and analysis methods because the complexity of such questions substantially exceeds human capabilities. Improvements can be achieved at the design phase of the system (Gramelsberger et al., 2023) or postponed to the execution phase of the system and be driven by, for example, digital twins (Tzachor et al., 2022), potentially augmented with machine learning techniques (Tomin et al., 2020). As current modeling languages typically do not explicitly support sustainability primitives, research is required to investigate how widely used modeling languages, such as AchiMate, BPMN, or SysML can be extended to i) accommodate sustainability properties (cf. (vom Brocke et al., 2012), (España et al., 2023)), and ii) represent these property values on an instant basis (i.e., how to enable models to represent the run-time state of the modeled system with respect to its sustainability properties). Alternatively, research can focus on the development of new modeling languages that consider sustainability not as an add-on but as a first-class citizen. Exemplifying this latter focus of research, we refer to (Gramelsberger et al., 2023) who extend an existing Architecture Description Language to allow for modeling systems, their sustainability properties, and sustainability questions in a structured manner. Only with such a treatment of sustainability within modeling languages, modeling can help in *improving* systems with respect to their sustainability.

The third role, *finding sustainability trade-offs*, becomes important after all previous roles have been filled. Sustainability goals are typically of a contradicting nature, and optimization of systems for sustainability — realistically — can be achieved only by finding and balancing the right trade-offs. This, of course, requires a thorough understanding of sustainability concepts (the first role) and modeling and optimization toolboxes to be readily available (the second role). Companies start to realize that corporate digital maturation should be coupled with corporate sustainability maturation — a concept commonly referred to as twin transition (World Economic Forum, 2022). Twin transition advocates for sustainable growth, and, as seen in the Degrowth and IT perspective of this panel, the desired direction of the growth, in some cases, might be pointing towards degrowth. Paths towards degrowth require changes not only in production processes (e.g. choosing renewable over non-renewable resources), and usage patterns (e.g. downshifting, reusing, repairing, sharing), but also at the marco-economic level (e.g. relocalizing production, democratizing economies, cultivating non-capitalist forms of economies). We can see implementations of these ideas in initiatives like the Bike Kitchen, where do-it-yourself bicycle repair studios are run on a non-profit basis in Sweden (Bradley, 2018). Also in Riversimple, a vehicle and mobility initiative that combines technological breakthroughs in hydrogen power with a circular business model and a collectivist, socially-framed governance structure (Wells, 2018). We expect an increase of initiatives and studies like these in the ICT domain. Some scholars have already focused on fundamental ICT infrastructure. For instance, Pansera et al. (2014) conduct a case study on the internet (especially data centers and submarine cables) and suggest a number of scenarios illustrating potential roles for such infrastructures in any planned reduction of economic activity. Fairphone, as a pioneer company in sustainable smartphone manufacturing, has also been subject to several case studies that unveil its thorough impact analyses, modular designs, and fair business models (Haucke, 2018; Romagnoli et al., 2022; Fischer et al., 2022; Rafi et al., 2024). Technological sufficiency, one of the main degrowth and ICT principles, is realized in initiatives such as solar-powered websites (Roscam Abbing, 2021). Finally, some scientific disciplines are reflecting on how degrowth should inform and influence their research avenues. For instance, Sharma et al. (2023) explore opportunities for the Human Computer Interaction community to take a post-growth orientation in research, design, and practice with the aim of reimagining the design of socio-technical systems enabling futures that are more sustainable, just, and humane. We call for a similar drive in the IS community.

Finally, the fourth role, *formalizing ethics*, emphasizes a role of modeling that augments technical and business perspectives. Modeling can help elicit, represent, and reason about the many systemic effects of sustainability and aid humans in sustainable decision-making (Cabot et al., 2009). It is, therefore, paramount to derive a detailed and precise view of the many systemic effects and trade-offs of sustainability and its goals which requires a formal specification by means of an ontological grounding. Once such an ontological grounding of the trade-offs is available, modeling goals can be centered around ethics, utility, fairness, and other sustainability principles, which ultimately enables the analysis and design of sustainable information systems (SIS) in sustainable ways (IS4S). The importance of incorporating notions of *value* into systems engineering has been long recognized (Lee & Paredis, 2014); however, filling this role requires radically novel formalisms, tools, languages, and engineering processes, as well as educating the next generation of (information) systems experts and prepare them for such a paradigm shift. An ongoing stream of research in formalizing ethical requirements is presented in (Guizzardi et al., 2023) where the authors propose a method to elicit and analyze ethicality requirements to support the precise definition of the concepts that underlie ethicality through an ontology. A recent review of the state of research on considering ethics in information systems and an agenda for future research are presented in (Bock et al., 2021).

6.2 Challenges in the Roles of Modeling: Conflicts Between Perspectives

The roles of modeling identified by the different perspectives are equally important. However, implementing them simultaneously is challenged by interdependencies and *conflicts* between perspectives (see Fig. 1). Here, we review some of these challenges that emerged during the panel.

The conflict between the *stakeholders* and *ethics* perspectives gives rise to the dilemma of *who to involve* in the decision-making about sustainability. On the one hand, democratization of sustainability decisions is clearly a desired direction from an ethical and societal viewpoint, as the increasing diversity of stakeholders contributes to more detailed and faithful notions of sustainability. On the other hand, with the increasing number of involved stakeholders, reaching consensus becomes more challenging. In this view, the understanding of sustainability is challenged by impractical democratization (as perceived from the Stakeholders perspective), while formalizing ethics is challenged by the pragmatic and possibly reductionist doctrines (as perceived from the Ethics perspective).

A potential resolution of the conflict are digital governance frameworks in which stakeholders can articulate their sustainability goals efficiently and their goals can be collected, collated, and operationalized to drive sustainable development of organizations. First strategies for digital governance strategies on a national level have been discussed in (Linkov et al., 2018). Translating these strategies for organizations will help in mitigating this conflict.

The conflict between *stakeholders* and *degrowth* gives rise to the dilemma whether reasoning about complex sustainability questions is feasible through human effort or advanced automation is required. Stakeholders are to be supported by advanced tools that help automate their reasoning and decision-making while seeking trade-offs between sustainability goals. However, degrowth ambitions might necessitate more human effort in taking the right actions. Degrowth ambitions challenge the understanding of sustainability by taking a reductionist stance on digitalization (as perceived from the Stakeholders perspectives), while the trade-offs finding role of modeling is challenged by overloading the decision-making with humans (as perceived from the Degrowth perspective).

A potential resolution of the conflict are sustainable computational methods, such as energy-efficient software (Chinnappan et al., 2021), approximate computing (Mittal, 2016), and Green AI (Verdecchia et al., 2023), which align with degrowth ambitions while they still support human stakeholders at appropriate levels.

The conflict between *digitalization* and *degrowth* gives rise to the dilemma of which direction twin transition (World Economic Forum, 2022) should take. Twin transition advocates sustainable growth by co-evolving the digital and sustainability maturity of organizations. Ideally, digitalization and sustainability maturity should reinforce each other and help organizations advance towards more sustainable systems and methods. While the Digitalization perspective advocates for accelerating twin transitions through advanced digitalization, the Degrowth perspective emphasizes avoiding accidental sustainability debt emerging from

unsustainable digital technology, such as AI and blockchain. Degrowth ambitions challenge the optimization and enactment roles of modeling (as perceived from the Digitalization perspective), while digitalization ambitions challenge the fairness of trade-offs advocated by the degrowth perspective — e.g., by biasing trade-offs towards digital transformation and omitting sustainability goals.
A potential resolution of the conflict are novel systems engineering practices, such as circular systems engineering (David, Bork, et al., 2023), in which the bipartite focus on sustainability demands the harmonization of system-level sustainability goals and method-level sustainability goals, and sustainable systems engineering, focusing on reuse and value retention in systems engineering (van der Aalst et al., 2023).

The conflict between *digitalization* and *ethics* gives rise to the dilemma whether automation or humanization of model-based reasoning should receive more emphasis. Ideally, social and technical goals should receive equal weight in sustainability decisions. Ethical dimensions, such as the ones discussed in Section 5 (beneficence, non-maleficence, autonomy, explicability, justice) need to be considered when digitalizing systems, e.g., to support the preservation of collective social goals. Digitalization, however, must remain efficient. Introducing convoluted concepts of ethics and human values into the reasoning about sustainability challenges the optimization role of modeling (as perceived from the Digitalization perspective); while omitting humans and not treating them as explicit first-class citizens in reasoning about sustainability challenges ethical integrity (as perceived from the Ethics perspective).
Potential resolutions of the conflict are modeling techniques capable of incorporating social, economic, and moral aspects (Lukyanenko et al., 2023; Sarioğlu et al., 2023); and maintaining a socio-technical view on systems (Bolte et al., 2022) in which social and technical goals receive equal attention.

7 Conclusion

In this paper, we reported on a panel discussion on the role of modeling in the design and analysis of sustainable systems, organized at the 28th Working Conference on Exploring Modeling Methods for Systems Analysis (EMMSAD), co-located with the 35th International Conference on Advanced Information Systems Engineering (CAiSE) in June 2023. By facilitating a discussion among experts representing four different perspectives – *stakeholders*, *digitalization*, *degrowth and IT*, and *ethics* – we identified key takeaways regarding the role of modeling in the design and analysis of sustainable systems: i) understanding the highly multi-systemic and stratified nature of sustainability; ii) optimizing, verifying, enacting, and monitoring sustainability properties; iii) understanding trade-offs among sustainability dimensions; and iv) formalizing relevant notions like ethical, juridical, and fairness principles. Appendix B collects and collates key actionable research directions articulated during the panel, along the scopes of humans, technologies, analysis, formalization & standardization, and education & cooperation. Our report contributes to the important topic of sustainable information systems (SIS) and their engineering by means of sustainable methods, techniques, and tools (IS4S). It aims to support scientists in steering research, and decision-makers in understanding the added layers of responsibility sustainability imposes on their decisions.

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Appendix A: Weak versus strong sustainability

Deciding what we mean by sustainability is, unfortunately, still a matter of discussion. As a scientific community we are yet debating how demanding are the conditions for sustainability. A first approach can be distinguishing two viewpoints on the concept of sustainability and the gap between the current level of sustainability of humanity's behavior. Bebbington et al. (2001) distinguish two viewpoints about this matter which, despite agreeing that our current behavior is not sustainable, differ in their interpretation of the current state of affairs, the goal of sustainability, and the preferred pathway to sustainability.

- **Weak sustainability** is concerned with preventing environmental catastrophes that would threaten human societies, since the human species is what we seek to sustain. The natural environment is seen as a resource that needs better management. Still, ecological issues have priority over social or intergenerational equity issues, since this viewpoint permeates and is fed by Western culture and therefore puts Western lifestyles and privileges in the forefront. Anyhow, the current state of affairs is almost sustainable and it should be possible to arrive at a sustainable state within half a century by means of technological innovation, substitution, and efficiency gains. To achieve this, we can resort to authoritative and coercive structures (e.g. market and governmental forces such as taxing resource extraction or pollution). All in all, economic development and growth are deemed essential for the pursuit of sustainability, in line with green growth stances.
- **Strong sustainability** calls for the re-examination of our relationship with the environment, where all species are to be maintained. Rather than seeing the natural environment as a resource, it seeks harmony between humans and nature, adopting stances closer to deep ecology. Intragenerational equity is essential to sustainability, and the needs and desires of developing economies are considered. The current state of affairs is deemed so far from a sustainable one, that it will take us a fundamental, structural change and two centuries to reach the latter, and it is even difficult to imagine how the pathway and the destination will look like. The process needs to

be participatory, transparent and democratic, and technology is in the background due to its many side effects and trade-offs. A shift towards post-growth socio-economic paradigms is needed.

For a more detailed discussion on these viewpoints, see also the work by Gray et al. (2014).

Appendix B: Research & Action Agenda Derived from the Discussion

Table 1. Potential directions of future research, identified by the panelists.

Scope	**Research directions identified in the panel**
Humans	● Develop strategies to identify all relevant stakeholders, their roles, and competencies. ● Define new languages, methods, and tools to include and engage these stakeholders. ● Realize ways for all stakeholders to define their sustainability requirements in a natural way while maintaining integrity to all other stakeholder views and handling potential conflicts.
Technologies	● Realize interoperable tools to facilitate seamless collaboration. ● Tame the digital divide by ensuring that the digital techniques are inclusive with respect to different cultural, economic, and ecological backgrounds.
Analysis	● Develop methods to analyze, monitor, and balance trade-offs between sustainability goals. ● Develop or adapt existing methods to reason about ethical dilemmas, connecting the reasoning process or its result to IT models. ● Investigate potentials to extend cause-effect techniques to cope with the specific characteristics of sustainability. ● Investigate potentials for degrowth of IT and degrowth by IT.
Formalization & Standardization	● Formalize sustainability characteristics. ● Develop standardized sustainability metrics. ● Support deep ontological/semantic analysis of sustainability-related notions. ● Integrate sustainability into modeling frameworks.
Education & Cooperation	● Integrate sustainability aspects into the IS and SE curricula (cf. INCOSE[10]). ● Establish awareness among students that sustainability is not an add-on but a first-class citizen during IS analysis and design. ● Encourage interdisciplinary cooperation among researchers, practitioners, and stakeholders from different fields by means of organizing workshops, symposia, Dagstuhl seminars, and summer schools.

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[10] https://www.incose.org/about-systems-engineering/se-vision-2035

About the Authors

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