Environmental Digital Twins: Connecting Models for Nature 5.0 (Keynote)

Einar Broch Johnsen
einarj@ifi.uio.no
University of Oslo
Oslo, Norway

Andrea Pferscher
andreapf@ifi.uio.no
University of Oslo
Oslo, Norway

Silvia Lizeth Tapia Tarifa
sltarifa@ifi.uio.no
University of Oslo
Oslo, Norway

Abstract

By connecting digital models and physical assets in real time, digital twins enable new levels of agility across industry for planning and optimization, as well as predictive maintenance. The recent vision of Industry 5.0 puts digital twin technology at the service of the green transition, emphasizing sustainable and human-centric goals for industry. But in fact, these goals also concern nature and how humans interact with nature. In this talk, we explore the potential of digital twins as a technology backbone for Nature 5.0, connecting digital models with natural systems in real-time - not only for environmental monitoring, but for long-term decision-making and sustainability. We discuss different aspects of engineering digital twins of ecosystems, including digital twin architectures, interoperability, model management, and self-adaptation, as well as challenges and opportunities in this interdisciplinary work. The talk will be illustrated by examples from our own work, such as the digital twin of the Oslofjord.

CCS Concepts

• **Software and its engineering** → **Software as a service orchestration system**; **Layered systems**; • **Computer systems organization** → **Self-organizing autonomic computing**.

Keywords

Digital Twins, Self-Adaptive Systems, Industry 5.0, Natural Environments, Environmental Monitoring, Socio-Technological Systems

ACM Reference Format:
Einar Broch Johnsen, Andrea Pferscher, and Silvia Lizeth Tapia Tarifa. 2026. Environmental Digital Twins: Connecting Models for Nature 5.0 (Keynote). In *ACM/IEEE 29th International Conference on Model Driven Engineering Languages and Systems (MODELS Companion 2026), October 04–09, 2026, Málaga, Spain.* ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3837062.3841441

1 Introduction

A digital twin is a dynamic virtual representation of a system that integrates models and continuously updated real-time data that comes from, e.g., sensors, operational systems, or historical records to support analysis such as diagnosis, fault detection, predictions, prescriptions, and decision-making [16, 24]. While digital twins emerged from engineering disciplines [6, 14], they are now increasingly being adopted in other domains where their value comes from their tight integration of models and the target system, which enables analytical support based on up-to-date models that integrate real-time data; while the initial notion that highlighted bidirectionality (i.e., the reactive control of a cyber-physical system) is becoming less and less prominent and may appear as a slower process involving, e.g., human-in-the-loop decision-making.

Industry 5.0 puts the digital transformation of industry (i.e., Industry 4.0) at the service of the green transition, emphasising sustainable and human-centric goals for industry [1, 19]. Here, innovations such as digital twins play a particularly important role by bringing data-driven decision-making to the forefront, enhancing efficiency and sustainability. Digital twins, combined with human modelling methods and real-time monitoring, enable explanations to protect humans while enhancing the performance of industrial assets. In this paper, we explore how these capabilities of digital twins can deliver service to natural environments: Can *environmental digital twins*, still in combination with human modelling methods and real-time monitoring (as illustrated by Fig. 1), provide a technological backbone for environmental governance and management, resulting in a notion of Nature 5.0 that supports agile, data-driven decision-making concerning the ecosystems around us and their management?

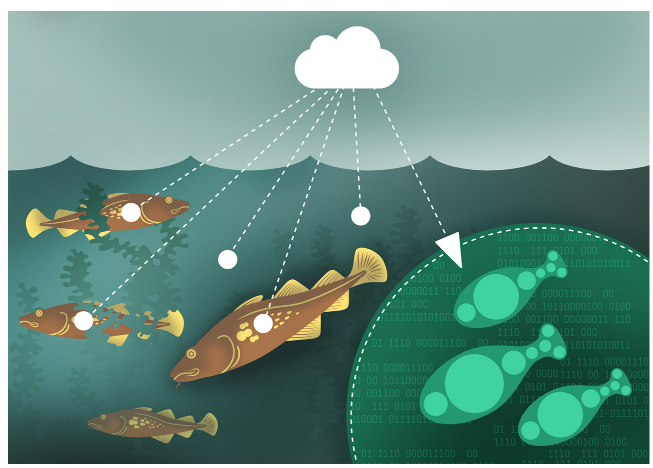

Figure 1: Our vision of Nature 5.0 uses environmental digital twins to connect models and ecosystems in real-time. The agile analysis capabilities of these systems can support the development and implementation of environmental policies, adapting to uncertainties caused by climate stressors.

ACM ISBN 979-8-4007-2903-4/2026/10
https://doi.org/10.1145/3837062.3841441

2 Challenges for Environmental Digital Twins

Digital twins in an industrial context tend to have a clear purpose (e.g., condition-based maintenance or control), sensors can be built into the asset at the key locations, and the engineering knowledge associated with the asset and with the twin's purpose is well understood. In contrast to industrial systems, natural environments are highly complex systems that are currently under pressure from climate change and human activities. Blair *et al.* [3] argue that the role of digital technologies for natural environments is to enable capabilities to deal with uncertainty and complexity while remaining open, transparent, and reproducible, which requires technologies that can cope with environmental challenges. Furthermore, Blair [2] also highlights that there is enormous potential of digital twins in natural environments since they can make behavioural models more dynamic by making them evolve, according to updates coming from data-driven analysis.

However, the adoption of digital twins for natural environments poses its own intrinsic challenges, including the monitoring of a continuous physical space without clearly defined key locations that includes hostile environments that cannot be fully covered by sensors, due to, e.g., extreme weather or difficult access, e.g., [15]. Moreover, domain expertise about natural environments is under constant development and affected by unknown factors that come from, e.g., climate change and human activities [8, 18]. Furthermore, environmental digital twins used for environmental monitoring and decision-making tend to be multi-purpose in the sense that they are explorative and need to give support to various stakeholders with diverse interests, e.g., environmental and data scientists, policy makers, etc. Hence in this paper, we consider the following three challenges for environmental digital twins:

- **Ch1:** How can a digital twin collect observational data from the continuous space of a natural environment?
- **Ch2:** How can an environmental digital twin integrate evolving domain expertise in the operational system?
- **Ch3:** How can an environmental digital twin adapt to explorative use?

This paper explores these challenges in the context of the ongoing interdisciplinary research project OsloFjordDT [17], which aims to develop a digital twin framework in which users can explore the effect of climate and human stressors on marine habitats in the Oslofjord.

3 An Environmental Digital Twin Architecture

Let us consider an environmental digital twin architecture that combines *observational data*, *knowledge bases*, and *analytics* to answer user queries via a *frontend.* This architecture is shown in Fig. 2, where an *orchestrator* is envisioned as an intermediate layer that configures information and models to answer the queries. OsloFjordDT works with this architectural framework and concretely aims to combine *real-time* data from sensors in the fjord (e.g., temperature and turbidity) and *simulated data* for locations where there is no data collection, with knowledge about biological aspects of the fjord system (e.g., biodiversity) to answer questions that will trigger different analytics such as *historical* (what happened in the past) and *descriptive* (what just happened) that could answer factual observations of the physical and biological aspects in the fjord, e.g., observed measurements of the physical conditions; while *predictive* (what do we expect to observe) and *prescriptive* (what can we do to change future observations) could help stakeholders to decide on, e.g., environmental policies based on predicted expected habitats at locations without direct data collection.

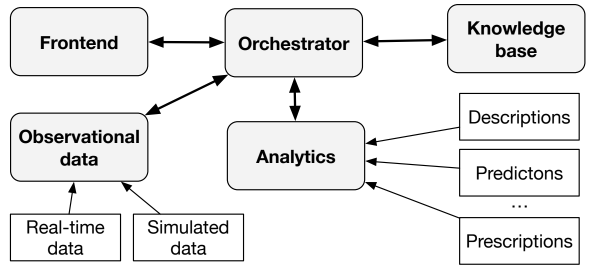

Figure 2: An architecture for Environmental Digital Twins.

4 Observational Data of Natural Environments

Accurately representing the current system state through the digital twin requires continuous data updates. Unlike industrial digital twins, creating an adequate data representation for environmental digital twins poses a challenge due to the extensive state space. Furthermore, the quantity of measurements can vary depending on the reliability of the sensors. Therefore, environmental digital twins require a mechanism to compensate for missing measurements.

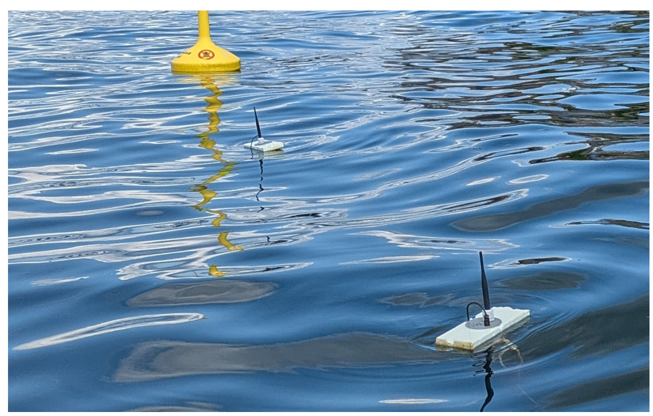

Figure 3: Floating buoys feed the OsloFjordDT with physical measurements in real-time.

For a holistic analysis, the OsloFjordDT combines real sensor measurements with measurements derived from underlying simulation models. The OsloFjordDT gathers real-time measurements via sensors in the fjord. Besides stationary sensors, floating sensors enable flexibility in the selection of interesting measuring points. The digital twin integrates a buoy network as described by Dreyer *et al.* [5] to measure physical parameters such as temperature. A deployment of the buoys in Oslofjord is shown Fig. 3. However, covering the whole environmental system with sensors is not feasible. Especially, if the orchestrator requests measurements at certain locations. Therefore, we introduce the concept of virtual

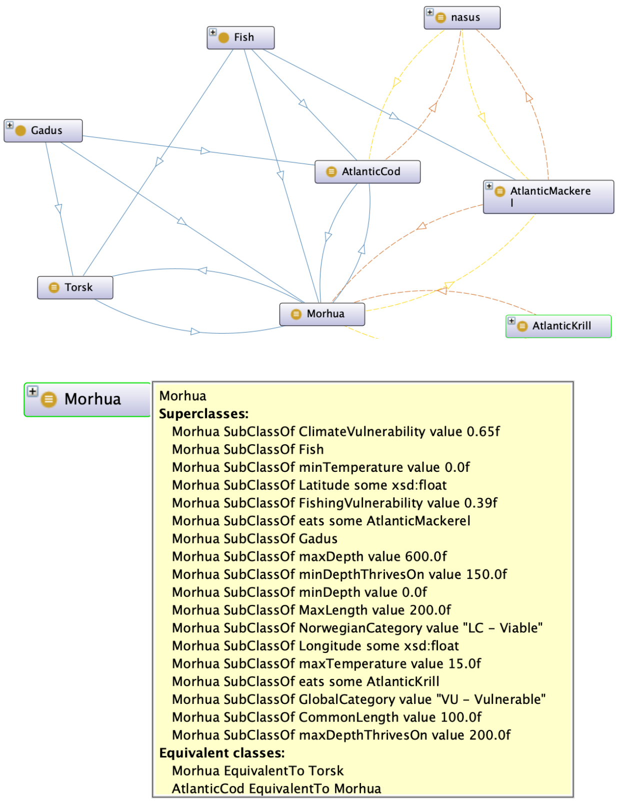

Figure 4: The representation of domain knowledge for the OsloFjordDT (snippet).

sensors that create measurements from simulation models. For the OsloFjordDT, we integrate simulations from the oceanographic model Norkyst [4], which allows to simulate physical measurements over a given period of time. For future work, it would be interesting to assimilate sensor readings into simulation models in order to create more accurate simulations.

5 Integrating Evolving Domain Expertise and Technological Expertise

Domain expertise and knowledge are often acquired directly from stakeholders; in the context of environmental systems, such knowledge is in principle not settled, with various unknowns that are continuously being investigated, and as such information varies across sources. In the context of the OsloFjordDT, domain expertise about biodiversity can be structured in an ontology; see Fig. 4, which can be used to construct a knowledge base that can capture scientific knowledge with clear sources, e.g., species in the Oslofjord and their marine habitats, according to, e.g., [7].

Following our proposed architecture in Sec. 3, the orchestrator in the OsloFjordDT could use semantic reflective capabilities [10], which enables systems to access their own runtime state as a knowledge base that, in combination with the external domain knowledge from the desired sources, can be used for decision-making. Results in this direction have explored the use of semantically reflected digital twins for decision-making [11, 21, 23], in particular for socio-technical systems with a human-in-the-loop [13, 20, 22]. Furthermore, semantic reflection could also be used for the management of lifecycles in the assets, e.g., to configure the analytics according to fluctuations of species along the different seasons of the year, or according to different life stages of the biodiversity species. Results in this direction have explored the use of semantically reflective digital twins that configure themselves according to declarative lifecycle stages [9, 21]. It is worth exploring how similar solutions can be applied to environmental digital twins.

Tackling the challenge of updates in the knowledge base, standard practices to update domain expertise require human interventions, making changes to domain expertise slow. To speed up this process, dedicated observational systems can be used to keep track of, e.g., new knowledge about species over time. Results in this direction explore the use of industrial computer vision models to do underwater explorations of the biodiversity in the Oslofjord [12].

6 Explorative Twins

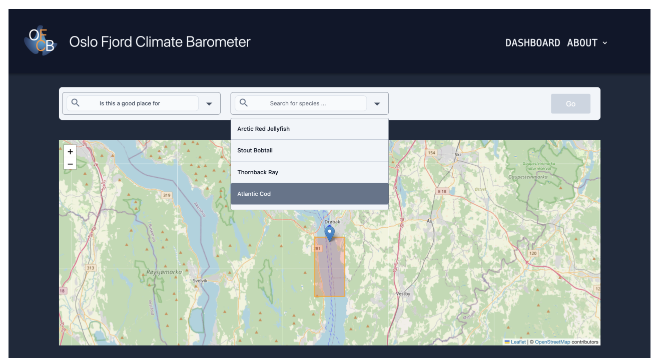

Figure 5: User-driven Interface for query-driven twin configurations.

Environmental digital twins represent socio-technical systems that provide insights for informed decision-making. The twins are explorative, as their purpose varies. Hence, insights from the digital twin must be tailored to the individual needs of the decision-makers. Figure 5 shows the interface of the OsloFjordDT, which allows its users to assemble individual queries. For this, we propose a framework that automatically synthesises monitors from the knowledge base to analyse the observational data [25]. Still, the challenge of implementing decisions in environmental system itself remains. For this, environmental digital twins need to integrate a human-in-the-loop perspective that automatically adapts to human enforced decisions as it has been in digital twins for resource management [22].

7 Conclusion

Natural environments are complex systems; digital technologies such as digital twins have the potential to enable analytical capabilities for historical, descriptive, predictive, and prescriptive analytics that can help stakeholders with decision-making, supporting the broader Nature 5.0 vision introduced in this paper. However, natural environments pose challenges that are inherited from their domain; in particular, the collection of observational data from an extensive physical space, the acquisition of unsettled domain expertise in a digital format that can be integrated and used in the analytical capabilities of a twin, and the need for digital twin technology that can be tailored to the specific needs of different stakeholders as an explorative tool. This paper discusses these challenges in the context of the OsloFjordDT, and shares initial results and future directions that can help to close the gap towards the vision of Nature 5.0, with solutions that have the potential to deal with known unknowns in the natural environments via simulated data, transparency of the analytics and reproducibility of the results that make use of knowledge bases with traceable facts. The solution space discusses an architecture that combines external domain knowledge and observational data through a semantically reflected orchestrator that uses them to configure the analytics to answer user queries.

Acknowledgement. This paper came together under strange circumstances in the wake of the solar eclipse 2026. Our work has benefited from collaboration with MarinReperatørene, the Norwegian Meteorological Institute, Sintef and the Dept. of Mathematics at the University of Oslo.

References

[1] João Barata and Ina Kayser. 2023. Industry 5.0 – Past, Present, and Near Future. *Procedia Computer Science* 219 (2023), 778–788. doi:10.1016/j.procs.2023.01.351 CENTERIS – International Conference on ENTERprise Information Systems / ProjMAN – International Conference on Project MANagement / HCist – International Conference on Health and Social Care Information Systems and Technologies 2022.

[2] Gordon S. Blair. 2021. Digital twins of the natural environment. *Patterns* 2, 10 (2021), 100359. doi:10.1016/J.PATTER.2021.100359

[3] Gordon S. Blair, Richard Bassett, Lucy Bastin, Lindsay Beevers, Maribel Isabel Borrajo, Mike Brown, Sarah L. Dance, Ada Dionescu, Liz Edwards, Maria Angela Ferrario, Rob Fraser, Harriet Fraser, Simon Gardner, Peter A. Henrys, Tony Hey, Stuart Homann, Chantal Huijbers, James Hutchison, Phil Jonathan, Rob Lamb, Sophie Laurie, Amber Leeson, David Leslie, Malcolm McMillan, Vatsala Nundloll, Oluwole K. Oyebamiji, Jordan Phillipson, Vicky Pope, Rachel Prudden, Stefan Reis, Maria Salama, Faiza Samreen, Dino Sejdinovic, Will Simm, Roger Street, Lauren Thornton, Ross Towe, Joshua Vande Hey, Massimo Vieno, Joanne A. Waller, and John Watkins. 2021. The Role of Digital Technologies in Responding to the Grand Challenges of the Natural Environment: The Windermere Accord. *Patterns* 2, 1 (2021), 100156. doi:10.1016/J.PATTER.2020.100156

[4] Kai Håkon Christensen, Jon Albretsen, Lars Asplin, Håvard Guldbrandsen Frøysa, Yvonne Gusdal, Silje Christine Iversen, Mari Fjalstad Jensen, Ingrid Askeland Johnsen, Nils Melsom Kristensen, Pål Næverlid Sævik, et al. 2026. “Norkyst” version 3: the coastal ocean forecasting system for Norway. *Geoscientific Model Development* 19, 7 (2026), 2785–2798.

[5] Lars Willas Dreyer, Andrea Pferscher, Riccardo Sieve, Jean Rabault, Atle Jensen, Einar Broch Johnsen, and Gaute Hope. 2026. ORB: An Open Radio Buoy for Coastal Water Measurements. arXiv:2601.05615 [physics.ao-ph] https://arxiv.org/abs/2601.05615

[6] John Fitzgerald, Cláudio Gomes, and Peter Gorm Larsen (Eds.). 2024. *The Engineering of Digital Twins*. Springer. doi:10.1007/978-3-031-66719-0

[7] Global Biodiversity Information Facility (GBIF). [n. d.]. Free and open access to biodiversity data. https://www.gbif.org. Accessed: 2026-08-12.

[8] Zeinab Ghaedi, Cristina Santos, and Cristina Monteiro. 2026. Nature-Based solutions, climate change, and biodiversity: A systematic review of opportunities and risks. *Nature-Based Solutions* 9 (2026), 100302. doi:10.1016/j.nbsj.2026.100302

[9] Eduard Kamburjan, Nelly Bencomo, Einar Broch Johnsen, and Silvia Lizeth Tapia Tarifa. 2026. Declarative Lifecycle Management for Self-Adaptive Systems. *Softw. Syst. Model.* 25, 3 (2026), 787–814. doi:10.1007/S10270-026-01358-W

[10] Eduard Kamburjan, Vidar Norstein Klungre, Yuanwei Qu, Rudolf Schlatte, Egor V. Kostylev, Martin Giese, and Einar Broch Johnsen. 2026. Semantically Reflected Programs. *TGDK* 4, 1 (2026), 3:1–3:52. doi:10.4230/TGDK.4.1.3

[11] Eduard Kamburjan, Riccardo Sieve, Chinmayi Prabhu Baramashetru, Marco Amato, Gianluca Barmina, Eduard Occhipinti, and Einar Broch Johnsen. 2024. GreenhouseDT: An Exemplar for Digital Twins *(SEAMS '24)*. Association for Computing Machinery, New York, NY, USA, 175–181. doi:10.1145/3643915.3644108

[12] Eduard Kamburjan, Laura A. Slaughter, Einar Broch Johnsen, Andrea Pferscher, and Laura Weihl. 2025. Towards Self-Adaptive Data Management in Digital Twins for Biodiversity Monitoring. In *28th ACM/IEEE International Conference on Model Driven Engineering Languages and Systems, MODELS 2025 - Companion, Grand Rapids, MI, USA, October 5-10, 2025*. IEEE, 257–263. doi:10.1109/MODELS-C68889.2025.00044

[13] Åsmund A. A. Kløvstad, Paul Kobialka, Riccardo Sieve, Andrea Pferscher, Laura Slaughter, Silvia Lizeth Tapia Tarifa, and Einar Broch Johnsen. 2026. What-If Scenarios for the BedreFlyt Digital Twin. In *Principles of formal quantitative analysis — Essays dedicated to Christel Baier on the occasion of her 60th birthday (LNCS, Vol. 15760)*. Springer, 360—-381. doi:10.1007/978-3-031-97439-7_18

[14] Werner Kritzinger, Matthias Karner, Georg Traar, Jan Henjes, and Wilfried Sihn. 2018. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine* 51, 11 (2018), 1016–1022. doi:10.1016/j.ifacol.2018.08.474

[15] Michael J. Murphy, Øystein Tveito, Eivind Flittie Kleiven, Issam Raïs, Eeva M. Soininen, John Markus Bjørndalen, and Otto J. Anshus. 2021. Experiences Building and Deploying Wireless Sensor Nodes for the Arctic Tundra. In *21st IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing, CCGrid 2021, Melbourne, Australia, May 10-13, 2021*. IEEE, 376–385. doi:10.1109/CCGRID51090.2021.00047

[16] National Academies of Sciences, Engineering, and Medicine. 2024. Foundational Research Gaps and Future Directions for Digital Twins. https://doi.org/10.17226/26894

[17] Department of Informatics University of Oslo. [n. d.]. Oslofjord DT. https://ebjohnsen.org/project/oslofjord/. Accessed: 2026-08-12.

[18] Petr Pyšek, Philip E. Hulme, Dan Simberloff, Sven Bacher, Tim M. Blackburn, James T. Carlton, Wayne Dawson, Franz Essl, Llewellyn C. Foxcroft, Piero Genovesi, Jonathan M. Jeschke, Ingolf Kühn, Andrew M. Liebhold, Nicholas E. Mandrak, Laura A. Meyerson, Aníbal Pauchard, Jan Pergl, Helen E. Roy, Hanno Seebens, Mark van Kleunen, Montserrat Vilà, Michael J. Wingfield, and David M. Richardson. 2020. Scientists' warning on invasive alien species. *Biological Reviews* 95, 6 (2020), 1511–1534. doi:10.1111/brv.12627

[19] Rame Rame, Purwanto Purwanto, and Sudarno Sudarno. 2024. Industry 5.0 and sustainability: An overview of emerging trends and challenges for a green future. *Innovation and Green Development* 3, 4 (2024), 100173. doi:10.1016/j.igd.2024.100173

[20] Riccardo Sieve, Nelly Bencomo, Einar Broch Johnsen, and Silvia Lizeth Tapia Tarifa. 2026. BedreFlyt Artifact: A Self-Adaptive Digital Twin Software System for Hospital Resource Allocation. To appear.

[21] Riccardo Sieve, Eduard Kamburjan, Ferruccio Damiani, and Einar Broch Johnsen. 2025. Declarative Dynamic Object Reclassification. In *39th European Conference on Object-Oriented Programming, ECOOP 2025, June 30 to July 2, 2025, Bergen, Norway (LIPIcs, Vol. 333)*. Schloss Dagstuhl - Leibniz-Zentrum für Informatik, 29:1–29:31. doi:10.4230/LIPICS.ECOOP.2025.29

[22] Riccardo Sieve, Paul Kobialka, Andrea Pferscher, Nelly Bencomo, Silvia Lizeth Tapia Tarifa, Buster Salomon Rasmussen, and Einar Broch Johnsen. 2026. A Self-Adaptive Digital Twin Architecture for Dynamic Resource Management. In *Proc. 21st Intl. Conf. on Software Engineering for Adaptive and Self-Managing Systems (SEAMS'26)*. ACM, 92–104. doi:10.1145/3788550.3794872

[23] Riccardo Sieve, Paul Kobialka, Laura Slaughter, Rudolf Schlatte, Einar Broch Johnsen, and Silvia Lizeth Tapia Tarifa. 2025. BedreFlyt: Improving Patient Flows through Hospital Wards with Digital Twins. In Proceedingsof the First International Workshop on *Autonomous Systems Quality Assurance and Prediction with Digital Twins,* Hamilton, Canada, 4th May 2025 *(Electronic Proceedings in Theoretical Computer Science, Vol. 418)*. Open Publishing Association, 1–15. doi:10.4204/EPTCS.418.1

[24] Karen Willcox and Brittany Segundo. 2024. The role of computational science in digital twins. *Nat. Comput. Sci.* 4, 3 (2024), 147–149. doi:10.1038/S43588-024-00609-4

[25] Åsmund Aqissiaq Arild Kløvstad, Riccardo Sieve, Andrea Pferscher, Eduard Kamburjan, Einar Broch Johnsen, and Martin Leucker. 2026. Knowledge-driven Stream Monitor Synthesis. In *Proc. 26th International Conference on Runtime Verification (RV 2026) (Lecture Notes in Computer Science)*. Springer. To appear.