Sunfish: Enabling Predictive Analytics for Datacenters Through Digital Twinning

M. Kwiatkowski Ph.D. D. Niewenhuis[1] Prof. Dr. A. Iosup[2]

[1]Daily Supervisor

[2]Main Supervisor

Vrije Universiteit Amsterdam

June 10, 2026

Context

Heterogeneous datacenter architectures are common [9] due to the end of Dennard's scaling [6]. Today, computational needs of AI drive managers to diversify datacenters even more [1]. In result datacenters become extremely complex and hard to operate.

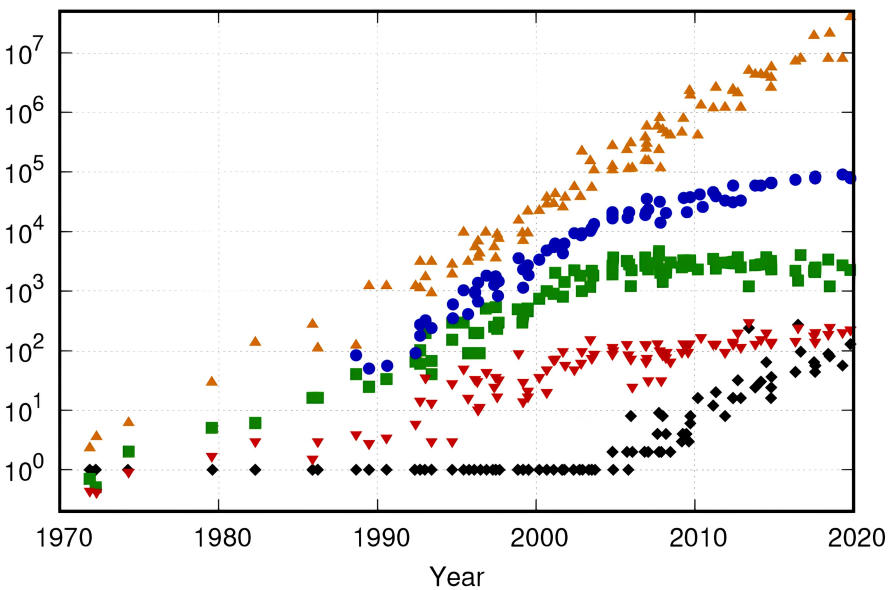

Figure 1.1: 48 years of microprocessor trend data. Legend: ▲ Transistors (thousands), ● Single Thread Performance (SpecINT 10^3), ■ Frequency (MHz), ▼ Typical Power (Watts), ◆ Number of Logical Cores [6].

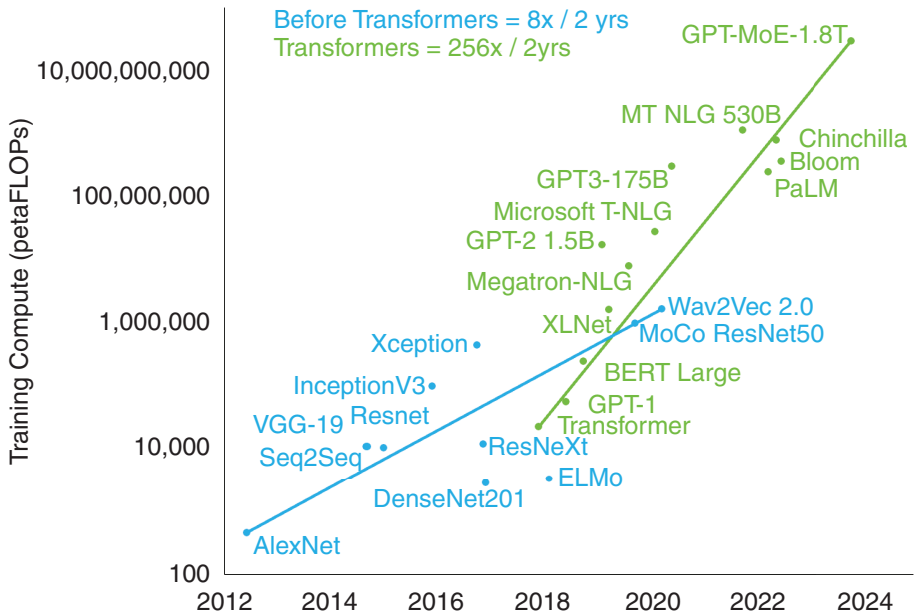

Figure 1.2: Explosive growth in AI computational requirements drives datacenter upgrades (source: NVIDIA Analysis: reproduction with NVIDIA permission by [1]).

Problem Statement

VRIJE UNIVERSITEIT AMSTERDAM

We need effective tools to manage datacenters

To address the increasing datacenter complexity, Datacenter Digital Twins (DCDT) were proposed [1]. However, many DCDT's are not useful in practice, because they lack critical features (*e.g.,* predictive analytics) native to the generic Digital Twin definition [10].

Project	Simulation Technique	Focus	Stakeholders	Highlighted Features
ExaDigiT [2]	CFD/HT	Energy Loss Prediction		
SmartDC [15]	CFD/HT, BIM, AI	Heat Modelling		
DyTwin [11]	Gaussian Process Regression, ML	Anomaly Detection		
ChatTwin [8]	**?**	Configuration Automation		
Reducio [3]	POD	Heat and Airflow Prediction		
NetGraph [5]	Graphs	Network Management		
Kalibre [14]	ML, CFD	Heat Modelling		

Table 1.1: Comparison of selected datacenter digital twins. **Features:** 3D = 3D Visualizations; CH = Cooling/Heat, PE = Power/Energy Consumption, F = Failures, N = Network, FS = FaaS, SE = Scenario Exploration, VP = Virtual Prorotyping, FD = Federation; **Tools:** AI = Artificial Intelligence, ML = Machine Learning, ODA = Operational Data Analysis; ✻ = Predictive Analysis; ⋆ = Descriptive Analysis, ◈ = Prescriptive Analysis.

Research Questions

VU VRIJE UNIVERSITEIT AMSTERDAM

Main Research Question

How to enable predictive analytics for datacenters through digital twinning?

Research Question 1

How to asses the current state-of-the-art of digital twinning for datacenters?

Research Question 2

How to design a datacenter digital twin reference architecture using discrete-event simulation and predictive data analytics?

Research Question 3

How to evaluate and validate a datacenter digital twin architecture in relation to system requirements?

RQ1: System Model

VU VRIJE UNIVERSITEIT AMSTERDAM

RQ2: Reference Architecture

RQ3: Experimental Results I

RQ3: Experimental Results II

Discussion

References I

Jyotika Athavale, Cullen E. Bash, Wesley Brewer, Matthias Maiterth, Dejan S. Milojicic, Harry Petty, and Soumyendu Sarkar.
Digital twins for data centers.
Computer, 57(10):151–158, 2024.
URL https://doi.org/10.1109/MC.2024.3436945.

Wesley Brewer, Matthias Maiterth, Vineet Kumar, Rafal P. Wojda, Sedrick Bouknight, Jesse Hines, Woong Shin, Scott Greenwood, David Grant, Wesley Williams, and Feiyi Wang.
A digital twin framework for liquid-cooled supercomputers as demonstrated at exascale.
In *Proceedings of the International Conference for High Performance Computing, Networking, Storage, and Analysis, SC 2024, Atlanta, GA, USA, November 17-22, 2024*, page 23. IEEE, 2024.
URL https://dl.acm.org/doi/10.1109/SC41406.2024.00029.

Zhiwei Cao, Ruihang Wang, Xin Zhou, and Yonggang Wen.
Reducio: model reduction for data center predictive digital twins via physics-guided machine learning.
In Jorge Ortiz, editor, *Proceedings of the 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, BuildSys 2022, Boston, Massachusetts, November 9-10, 2022*, pages 1–10. ACM, 2022.
URL https://doi.org/10.1145/3563357.3564050.

Douglas Donnellan, Andy Lawrence, and Rose Weinshenk.
Executive summary: Annual outage analysis 2025, May 2025.
URL https://uptimeinstitute.com/resources/research-and-reports/annual-outage-analysis-2025.

Hanshu Hong, Qin Wu, Feng Dong, Wei Song, Ronghua Sun, Tao Han, Cheng Zhou, and Hongwei Yang.
Netgraph: An intelligent operated digital twin platform for data center networks.
In *NAI'21: Proceedings of the ACM SIGCOMM 2021 Workshop on Network-Application Integration, Virtual Event, USA, August 27, 2021*, pages 26–32. ACM, 2021.
URL https://doi.org/10.1145/3472727.3472802.

References II

M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten.

48 years of microprocessor trend data, 2019.
URL https://github.com/karlrupp/microprocessor-trend-data.

Alexandru Iosup, Fernando Kuipers, Ana Lucia Varbanescu, Paola Grosso, Animesh Trivedi, Jan S. Rellermeyer, Lin Wang, Alexandru Uta, and Francesco Regazzoni.

Future computer systems and networking research in the netherlands: A manifesto.
CoRR, abs/2206.03259, 2022.
URL https://doi.org/10.48550/arXiv.2206.03259.

Minghao Li, Ruihang Wang, Xin Zhou, Zhaomeng Zhu, Yonggang Wen, and Rui Tan.

Chattwin: Toward automated digital twin generation for data center via large language models.
In *Proceedings of the 10th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, BuildSys 2023, Istanbul, Turkey, November 15-16, 2023*, pages 208–211. ACM, 2023.
URL https://doi.org/10.1145/3600100.3623719.

Dejan S. Milojicic, Paolo Faraboschi, Nicolas Dubé, and Duncan Roweth.

Future of HPC: diversifying heterogeneity.
In *Design, Automation & Test in Europe Conference & Exhibition, DATE 2021, Grenoble, France, February 1-5, 2021*, pages 276–281. IEEE, 2021.
URL https://doi.org/10.23919/DATE51398.2021.9474063.

National Academy of Engineering, National Academies of Sciences Engineering, and Medicine.

Foundational research gaps and future directions for digital twins.
The National Academies Press, Washington, DC, 2024.
ISBN 978-0-309-70042-9.
URL https://nap.nationalacademies.org/catalog/26894/foundational-research-gaps-and-future-directions-for-digital-twins.

References III

Ebad Taheri, Pedro Bruel, Pavana Prakash, Gourav Rattihalli, Ninad Hogade, Aditya Dhakal, Rolando P. Hong Enriquez, Torsten Wilde, Leo Popokh, Dejan S. Milojicic, and Cullen E. Bash.
Dytwin: Federated adaptive digital twins for data centers - visualization and anomaly detection.
In *SC24-W: Workshops of the International Conference for High Performance Computing, Networking, Storage and Analysis , Atlanta, GA, USA, November 17-22, 2024*, pages 847–852. IEEE, 2024.
URL https://doi.org/10.1109/SCW63240.2024.00120.

Sacheendra Talluri, Leon Overweel, Laurens Versluis, Animesh Trivedi, and Alexandru Iosup.
Empirical characterization of user reports about cloud failures.
In Esam El-Araby, Vana Kalogeraki, Danilo Pianini, Fr édéric Lassabe, Barry Porter, Sona Ghahremani, Ingrid Nunes, Mohamed Bakhouya, and Sven Tomforde, editors, *IEEE International Conference on Autonomic Computing and Self-Organizing Systems, ACSOS 2021, Washington, DC, USA, September 27 - Oct. 1, 2021*, pages 158–163. IEEE, 2021.
URL https://doi.org/10.1109/ACSOS52086.2021.00039.

Fei Tao, Meng Zhang, Yushan Liu, and A.Y.C. Nee.
Digital twin driven prognostics and health management for complex equipment.
CIRP Annals, 67(1):169–172, 2018.
ISSN 0007-8506.
URL https://www.sciencedirect.com/science/article/pii/S0007850618300799.

Ruihang Wang, Xin Zhou, Linsen Dong, Yonggang Wen, Rui Tan, Li Chen, Guan Wang, and Feng Zeng.
Kalibre: Knowledge-based neural surrogate model calibration for data center digital twins.
In *BuildSys '20: The 7th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, Virtual Event, Japan, November 18-20, 2020*, pages 200–209. ACM, 2020.
URL https://doi.org/10.1145/3408308.3427982.

References IV

Ziting Zhang, Yu Zeng, Haoran Liu, Chaoyue Zhao, Feng Wang, and Yunqing Chen.

Smart DC: an AI and digital twin-based energy-saving solution for data centers.

In *2022 IEEE/IFIP Network Operations and Management Symposium, NOMS 2022, Budapest, Hungary, April 25-29, 2022*, pages 1–6. IEEE, 2022.

URL https://doi.org/10.1109/NOMS54207.2022.9789853.

Extra Slides: Societal Impact

Why is this research important today?

Over 3 million jobs in the Netherlands directly depend on cloud services, which are hosted in datacenters [7]. Already the rapid expansion of datacenters has increased the presence of service failures across all cloud services [12]. We need to act now.

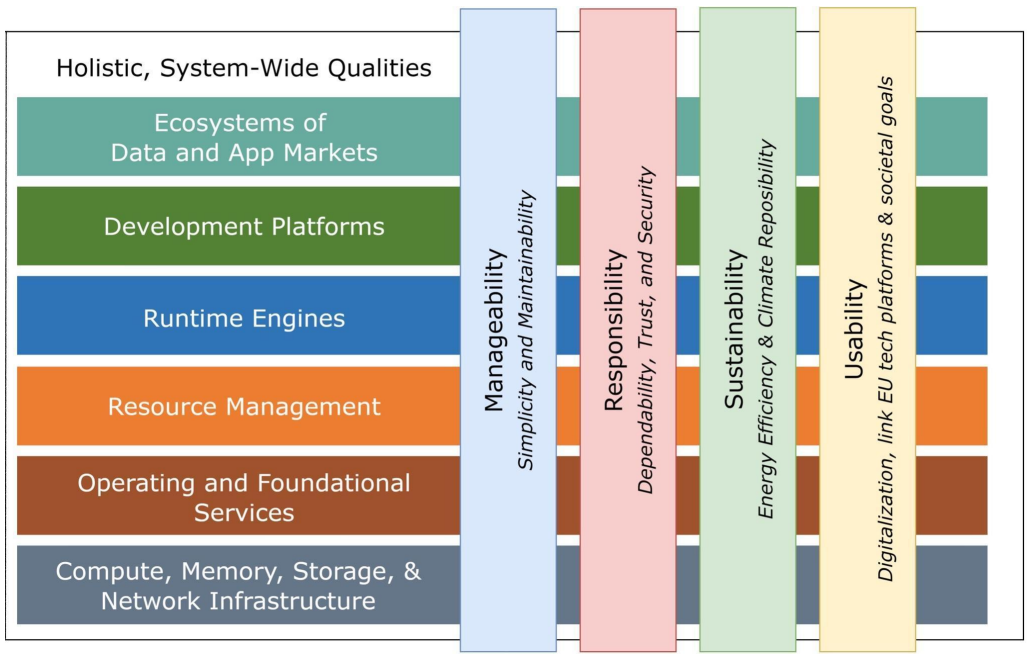

Figure E.1: Horizontally: the most important research areas in computer science in Netherlands. Vertically: qualities we should ensure across all research areas with the most outstanding impact on society. Datacenter manageability is a top-priority [7].

Extra Slides: Why Digital Twinning?

Definition

A DCDT mirrors the structure, context and behaviour of a datacenter [1]. The prerequisite to any digital twin is good monitoring and sensing capabilities in the physical entity. Datacenters meet this requirement easily because they already connect hundreds of monitoring sensors.

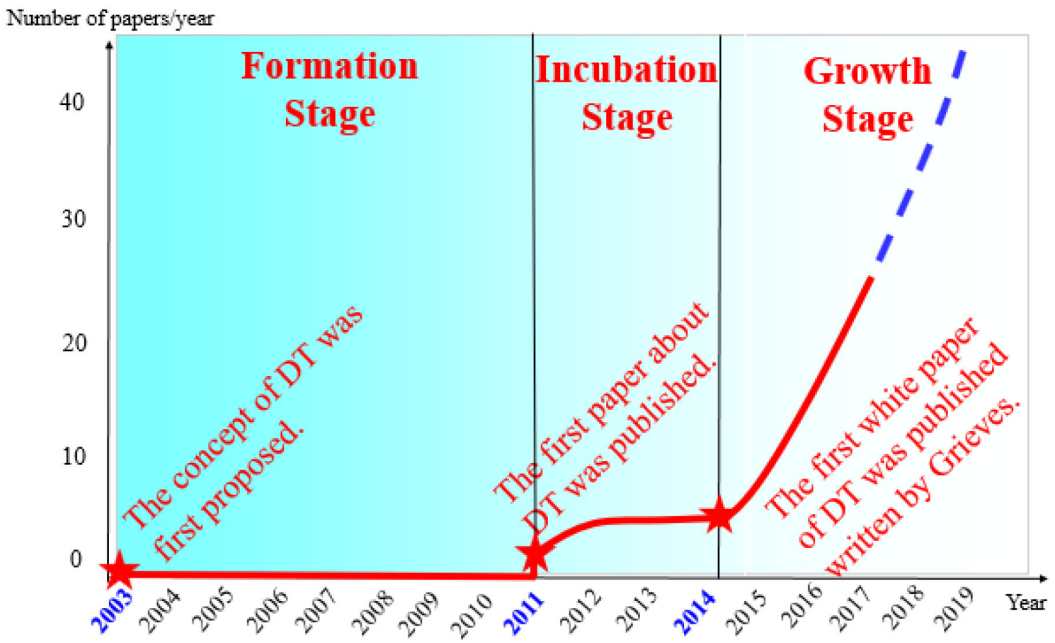

Figure E.2: Due to insufficient technological foundations, little work is available on DTs between 2003 and 2018, and it is only with the rapid growth of cloud computing, Internet-of-Things and Big Data analytics that DTs have reemerged [13]. That is why nobody used digital twins to mirror datacenters earlier.

Extra Slides: Why *not* pure simulation?

Predicting job failures

Preventing failure-caused outages in advance can reduce huge operational costs, as over 20% of all reported outages amount to more than 1 million US$ [4]. Only a constant bi-directional interaction (digital twin $\Longleftrightarrow$ physical entity) can achieve this.

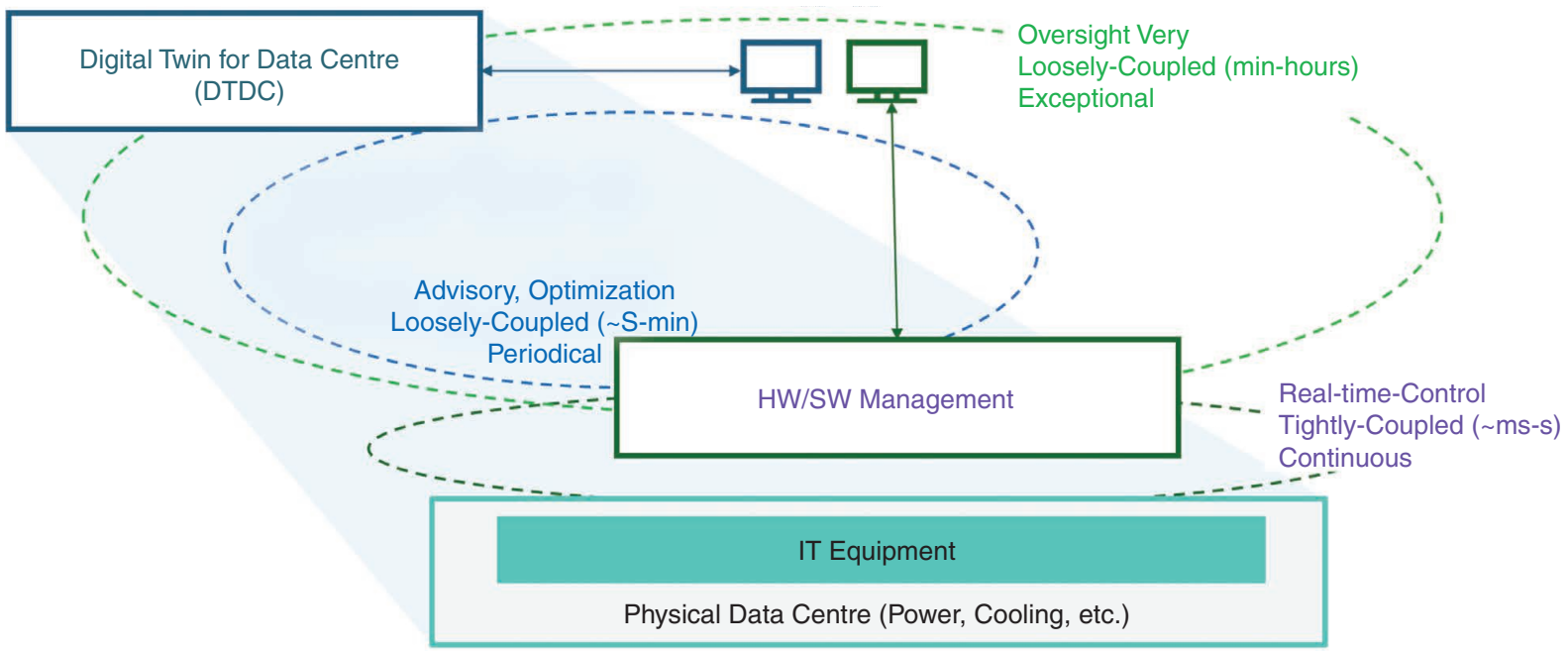

Figure E.3: Real-time control that is tightly-coupled with the IT equipment is a prerequisite for timely predictions within seconds/minutes [1].