

Literature Collection of Digital Twin Definitions from Various Domains

Birgit Vogel-Heuser*^a, Fandi Bi^a, Moritz Wittemer^b, Jingyun Zhao^a, Andreas Mayr^c, Martin Fleischer^d, Theresa Prinz^d, Anne Fischer^e, Jakob Trauer^f, Philipp Schröder^f, Ann-Kathrin Goldbach^g, Florian Rothmeyer^e, Markus Zimmermann^f, Kai-Uwe Bletzinger^g, Johannes Fottner^e, Rüdiger Daub^e, Klaus Bengler^d, André Borrmann^h, Michael F. Zäh^e, Katrin Wudy^b

^a Institute of Automation and Information Systems,

^b Professorship of Laser-based Additive Manufacturing,

^c Institute for Machine Tools and Industrial Management,

^d Chair of Ergonomics,

^e Chair of Materials Handling, Material Flow, Logistics,

^f Laboratory for Product Development and Lightweight Design,

^g Chair of Structural Analysis,

^h Chair of Computational Modeling and Simulation,

*corresponding author, all authors affiliated with the Technical University of Munich, TUM School of Engineering & Design, ^{a-f}: Boltzmannstr. 15, 85748 Garching, Germany,

^{g-h}: Arcisstr. 21, 80333 Munich, Germany

Keywords:

Digital Twin, Systems Integration, Engineering, Construction, Production, Manufacturing, Human, System of Systems, Industry 4.0

The following literature list forms the foundation for the cross-domain valid definition of a digital twin. This definition was developed in the scope of a separate publication and states:

Digital Twins are defined as dynamic digital representations of specific real-world entities consisting of (interlinked) components and interfaces with application-specific attributes and scales (e.g., time, size, accuracy, hierarchy, life cycle phase). Digital twins have the goal of recurrent improvement in the real world.

Literature list:

- [1] ISO/TC 184/SC 4, ISO 23247-1:2021, Automation systems and integration - Digital twin framework for manufacturing
- [2] 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference & BR&G;20th AIAA/ASME/AHS Adaptive Structures Conference & BR&G;14th AIAA, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2012.
- [3] 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2013.
- [4] 2016 IEEE International Conference on Autonomic Computing (ICAC), IEEE, 2016.
- [5] 54th AIAA Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2016.
- [6] AIAA SPACE 2016, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2016.
- [7] R. Al-Sehrawy, B. Kumar, Digital Twins in Architecture, Engineering, Construction and Operations. A Brief Review and Analysis, in: E. Toledo Santos, S. Scheer (Eds.), Proceedings of the 18th International Conference on Computing in Civil and Building Engineering, Springer International Publishing, Cham, 2021, pp. 924–939.
- [8] J. Arora, M. Tushir, Digital Twin, in: G. Chaudhary, M. Khari, M. Elhoseny (Eds.), Digital Twin Technology, CRC Press, Boca Raton, 2021, pp. 23–45.
- [9] E. Ayerbe, M. Bercibar, S. Clark, A.A. Franco, J. Ruhland, Digitalization of Battery Manufacturing: Current Status, Challenges, and Opportunities, *Advanced Energy Materials* 12 (2022) 2102696. <https://doi.org/10.1002/aenm.202102696>.
- [10] G. Bacchiega, Developing an embedded digital twin for HVAC device diagnostics, See https://irweb.it/pdf/Embedded_Digital%20Twin_HVAC_.pdf (2017).
- [11] M. Bajaj, B. Cole, D. Zwemer, Architecture To Geometry - Integrating System Models With Mechanical Design, in: AIAA SPACE 2016, Long Beach, California, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2016.
- [12] Y. Bazilevs, X. Deng, A. Korobenko, F. Di Lanza Scalea, M.D. Todd, S.G. Taylor, 2015. Isogeometric Fatigue Damage Prediction in Large-Scale Composite Structures Driven by Dynamic Sensor Data. *Journal of Applied Mechanics* 82, 091008. <https://doi.org/10.1115/1.4030795>.
- [13] T. Bergs, S. Gierlings, T. Auerbach, A. Klink, D. Schraknepper, T. Augspurger, The Concept of Digital Twin and Digital Shadow in Manufacturing, *Procedia CIRP* 101 (2021) 81–84. <https://doi.org/10.1016/j.procir.2021.02.010>.
- [14] Birgit Boss (Robert Bosch GmbH), Somayah Malakuti (ABB Corporate Research Center, Germany), Shi-Wan Lin (Yo-i), Thomas Usländer (Fraunhofer IOSB), Erich Clauer (SAP), Michael Hoffmeister (Festo SE & Co. KG), Ljiljana Stojanovic, Digital Twin and Asset Administration Shell Concepts and Application in the Industrial Internet and Industrie 4.0 (2020).
- [15] Bob Piascik, John Vickers, Dave Lowry, Steve Scotti, Jeff Stewart, Anthony Calomino, DRAFT Materials, Structures, Draft Materials, Structures, Mechanical Systems, and Manufacturing Roadmap, 210.
- [16] C. Boje, A. Guerriero, S. Kubicki, Y. Rezgui, Towards a semantic Construction Digital Twin: Directions for future research, *Automation in Construction* 114 (2020) 103179. <https://doi.org/10.1016/j.autcon.2020.103179>.

- [17] A. Bolton, L. Butler, I. Dabson, M. Enzer, M. Evans, T. Fenemore, F. Harradence, E. Keaney, A. Kemp, A. Luck, N. Pawsey, S. Saville, J. Schooling, M. Sharp, T. Smith, J. Tennison, J. Whyte, A. Wilson, C. Makri, Gemini Principles, CDBB, 2018.
- [18] R.N. Bolton, J.R. McColl-Kennedy, L. Cheung, A. Gallan, C. Orsingher, L. Witell, M. Zaki, Customer experience challenges: bringing together digital, physical and social realms, *JOSM* 29 (2018) 776–808. <https://doi.org/10.1108/JOSM-04-2018-0113>.
- [19] S. Chatti, T. Tolio (Eds.), *CIRP Encyclopedia of Production Engineering*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2019.
- [20] S. Chatti, T. Tolio (Eds.), *CIRP Encyclopedia of Production Engineering*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2019.
- [21] G. Chaudhary, M. Khari, M. Elhoseny (Eds.), *Digital Twin Technology*, CRC Press, Boca Raton, 2021.
- [22] A. Christ, P. Koch, M. Krastel, S. Schweigert-Recksiek, J. Trauer, Ready or not – the Digital Twin is coming! How can companies prepare for it?, *ProductData Journal* 29 (2022) 12–17.
- [23] M. Eigner, A. Detzner, P.H. Schmidt, R. Tharma, Definition des Digital Twin im Produktlebenszyklus, *Zeitschrift für wirtschaftlichen Fabrikbetrieb* 114 (2019) 345–350. <https://doi.org/10.3139/104.112107>.
- [24] C. Feng, T. Linner, I. Brilakis, D. Castro, P.-H. Chen, Y. Cho, J. Du, S. Ergan, B. Garcia de Soto, J. Gašparík, F. Habbal, A. Hammad, K. Iturralde, T. Bock, S. Kwon, Z. Lafhaj, N. Li, C.-J. Liang, B. Mantha, M.S. Ng, D. Hall, M. Pan, W. Pan, F. Rahimian, B. Raphael, A. Sattineni, C. Schlette, I. Shabtai, X. Shen, P. Tang, J. Teizer, Y. Turkan, E. Valero, Z. Zhu (Eds.), *Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC)*, International Association for Automation and Robotics in Construction (IAARC), 2021.
- [25] C. Feng, T. Linner, I. Brilakis, D. Castro, P.-H. Chen, Y. Cho, J. Du, S. Ergan, B. Garcia de Soto, J. Gašparík, F. Habbal, A. Hammad, K. Iturralde, T. Bock, S. Kwon, Z. Lafhaj, N. Li, C.-J. Liang, B. Mantha, M.S. Ng, D. Hall, M. Pan, W. Pan, F. Rahimian, B. Raphael, A. Sattineni, C. Schlette, I. Shabtai, X. Shen, P. Tang, J. Teizer, Y. Turkan, E. Valero, Z. Zhu (Eds.), *Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC)*, International Association for Automation and Robotics in Construction (IAARC), 2021.
- [26] H. Feng, Q. Chen, B. Garcia de Soto, Application of digital twin technologies in construction: an overview of opportunities and challenges, in: *Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC)*, Dubai, UAE, International Association for Automation and Robotics in Construction (IAARC), 2021.
- [27] A. Fuller, Z. Fan, C. Day, C. Barlow, Digital Twin: Enabling Technologies, Challenges and Open Research, *IEEE Access* 8 (2020) 108952–108971. <https://doi.org/10.1109/ACCESS.2020.2998358>.
- [28] T. Gabor, L. Belzner, M. Kiermeier, M.T. Beck, A. Neitz, A Simulation-Based Architecture for Smart Cyber-Physical Systems, in: *2016 IEEE International Conference on Autonomic Computing (ICAC)*, Wuerzburg, Germany, IEEE, 2016, pp. 374–379.
- [29] E. Glaessgen, D. Stargel, The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles, in: *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference & 20th AIAA/ASME/AHS Adaptive Structures Conference & 14th AIAA*, Honolulu, Hawaii, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2012.
- [30] B. Gockel, A. Tudor, M. Brandyberry, R. Penmetsa, E. Tuegel, Challenges with Structural Life Forecasting Using Realistic Mission Profiles, in: *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference & 20th AIAA/ASME/AHS Adaptive Structures Conference & 14th AIAA*, Honolulu, Hawaii, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2012.
- [31] S. Henschel, S. Otte, D. Mayer, J. Fleischer, Use Cases for Digital Twins in Battery Cell Manufacturing, in: M. Liewald, A. Verl, T. Bauernhansl, H.-C. Möhring (Eds.), *Production at the Leading Edge of Technology*, Springer International Publishing, Cham, 2023, pp. 833–842.
- [32] M. Huber, The potential of digital twins (orig. Das Potential digitaler Zwillinge), *Fachhochschule Nordwestschweiz FHNW*, 2019.
- [33] Jakob Beetz, Léon van Berlo, André Borrmann, Mark Enzer, Christian Frey, Ulrich Hartmann, Wolfgang Hass, Aidan Mercer, Frank Weiß, Natalie Weiß, *Enabling an Ecosystem of Digital Twins* (2020).
- [34] A. Kantaros, D. Piromalis, G. Tsaramiris, P. Papageorgas, H. Tamimi, 3D Printing and Implementation of Digital Twins: Current Trends and Limitations, *ASI* 5 (2022) 7. <https://doi.org/10.3390/asi5010007>.
- [35] E.M. Kraft, The Air Force Digital Thread/Digital Twin - Life Cycle Integration and Use of Computational and Experimental Knowledge, in: *54th AIAA Aerospace Sciences Meeting*, San Diego, California, USA, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2016.
- [36] J. Krauß, A. Krepplein, K. Pouls, T. Ackermann, A. Fitzner, A.D. Kies, J.-P. Abramowski, T. Hülsmann, D. Roth, A. Schmetz, C. Baum, Digital Twins in Battery Cell Production, in: M. Liewald, A. Verl, T. Bauernhansl, H.-C. Möhring (Eds.), *Production at the Leading Edge of Technology*, Springer International Publishing, Cham, 2023, pp. 823–832.

- [37] W. Kritzinger, M. Karner, G. Traar, J. Henjes, W. Sihn, Digital Twin in manufacturing: A categorical literature review and classification, *IFAC-PapersOnLine* 51 (2018) 1016–1022. <https://doi.org/10.1016/j.ifacol.2018.08.474>.
- [38] J. Lee, E. Lapira, B. Bagheri, H. Kao, Recent advances and trends in predictive manufacturing systems in big data environment, *Manufacturing Letters* 1 (2013) 38–41. <https://doi.org/10.1016/j.mfglet.2013.09.005>.
- [39] M. Liewald, A. Verl, T. Bauernhansl, H.-C. Möhring (Eds.), *Production at the Leading Edge of Technology*, Springer International Publishing, Cham, 2023.
- [40] M. Lutz, M. Münch, A. Turgut, D. Lucke, D. Palm, A. Braun, P. Ohlhausen, The digital twin along the product life cycle (orig. Der Digitale Zwilling entlang des Produktlebenszyklus), *Zeitschrift für wirtschaftlichen Fabrikbetrieb* 115 (2020) 422–424. <https://doi.org/10.3139/104.112314>.
- [41] P.K. Majumdar, M. FaisalHaider, K. Reifsnider, Multi-physics Response of Structural Composites and Framework for Modeling Using Material Geometry, in: 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Boston, Massachusetts, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2013.
- [42] M. Mikell, J. Clark, Cheat sheet: What is Digital Twin?, 2018.
- [43] E. Negri, L. Fumagalli, M. Macchi, A Review of the Roles of Digital Twin in CPS-based Production Systems, *Procedia Manufacturing* 11 (2017) 939–948. <https://doi.org/10.1016/j.promfg.2017.07.198>.
- [44] A.C. Ngandjong, T. Lombardo, E.N. Primo, M. Chouchane, A. Shodiev, O. Arcelus, A.A. Franco, Investigating electrode calendaring and its impact on electrochemical performance by means of a new discrete element method model: Towards a digital twin of Li-Ion battery manufacturing, *Journal of Power Sources* 485 (2021) 229320. <https://doi.org/10.1016/j.jpowsour.2020.229320>.
- [45] A. Parrot, L. Warsaw, *Industry 4.0 and the digital twin*, 2017.
- [46] A. Rasheed, O. San, T. Kvamsdal, Digital Twin: Values, Challenges and Enablers From a Modeling Perspective, *IEEE Access* 8 (2020) 21980–22012. <https://doi.org/10.1109/access.2020.2970143>.
- [47] K.S.D. Ravi, M.S. Ng, J. Medina Ibáñez, D.M. Hall, Real-time Digital Twin of Robotic construction processes in Mixed Reality, in: *Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC)*, Dubai, UAE, International Association for Automation and Robotics in Construction (IAARC), 2021.
- [48] K. Reifsnider, P. Majumdar, Multiphysics Stimulated Simulation Digital Twin Methods for Fleet Management, in: 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Boston, Massachusetts, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2013.
- [49] R. Rosen, G. von Wichert, G. Lo, K.D. Bettenhausen, About The Importance of Autonomy and Digital Twins for the Future of Manufacturing, *IFAC-PapersOnLine* 48 (2015) 567–572. <https://doi.org/10.1016/j.ifacol.2015.06.141>.
- [50] R. Sacks, I. Brilakis, E. Pikas, H.S. Xie, M. Girolami, Construction with digital twin information systems, *DCE* 1 (2020). <https://doi.org/10.1017/dce.2020.16>.
- [51] B. Schleich, N. Anwer, L. Mathieu, S. Wartzack, Shaping the digital twin for design and production engineering, *CIRP Annals* 66 (2017) 141–144. <https://doi.org/10.1016/j.cirp.2017.04.040>.
- [52] G.N. Schroeder, C. Steinmetz, C.E. Pereira, D.B. Espindola, Digital Twin Data Modeling with AutomationML and a Communication Methodology for Data Exchange, *IFAC-PapersOnLine* 49 (2016) 12–17. <https://doi.org/10.1016/j.ifacol.2016.11.115>.
- [53] R. Stark, T. Damerau, Digital Twin, in: S. Chatti, T. Tolio (Eds.), *CIRP Encyclopedia of Production Engineering*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2019, pp. 1–8.
- [54] M. Thomitzek, O. Schmidt, G. Ventura Silva, H. Karaki, M. Lippke, U. Krewer, D. Schröder, A. Kwade, C. Herrmann, Digitalization Platform for Mechanistic Modeling of Battery Cell Production, *Sustainability* 14 (2022) 1530. <https://doi.org/10.3390/su14031530>.
- [55] E. Toledo Santos, S. Scheer (Eds.), *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering*, Springer International Publishing, Cham, 2021.
- [56] J. Trauer, S. Schweigert-Recksiek, C. Engel, K. Spreitzer, M. Zimmermann, What is a digital twin? – Definitions and insights from an industrial case study in technical product development, *Proc. Des. Soc.: Des. Conf.* 1 (2020) 757–766. <https://doi.org/10.1017/dsd.2020.15>.
- [57] E. Tuegel, The Airframe Digital Twin: Some Challenges to Realization, in: 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference & 20th AIAA/ASME/AHS Adaptive Structures Conference & 14th AIAA, Honolulu, Hawaii, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2012.
- [58] Verband der Automobilindustrie, *Smart data in automotive production*, 2020.
- [59] C. Verdouw, B. Tekinerdogan, A. Beulens, S. Wolfert, Digital twins in smart farming, *Agricultural Systems* 189 (2021) 103046. <https://doi.org/10.1016/j.agry.2020.103046>.
- [60] F.M. Zanotto, D.Z. Dominguez, E. Ayerbe, I. Boyano, C. Burmeister, M. Duquesnoy, M. Eisentraeger, J.F. Montaña, A. Gallo-Bueno, L. Gold, F. Hall, N. Kaden, B. Muerkens, L. Otaegui, Y. Reynier, S. Stier, M. Thomitzek, A. Turetskyy, N.

- Vallin, J. Wessel, X. Xu, J. Abbasov, A.A. Franco, Data Specifications for Battery Manufacturing Digitalization: Current Status, Challenges, and Opportunities, *Batteries & Supercaps* 5 (2022). <https://doi.org/10.1002/batt.202200224>.
- [61] L. Zhang, X. Chen, W. Zhou, T. Cheng, L. Chen, Z. Guo, B. Han, L. Lu, Digital Twins for Additive Manufacturing: A State-of-the-Art Review, *Applied Sciences* 10 (2020) 8350. <https://doi.org/10.3390/app10238350>.