# Complex Network Modelling and Knowledge Graphs for Digital Twins and Industry 4.0

Patrick Berry and Madhushi Bandara



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# Complex Network Modelling and Knowledge Graphs for Digital Twins and Industry 4.0

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**Patrick Berry[1,*], Madhushi Bandara[2]**
*1 School of Computer Science, FEIT, University of Technology Sydney, Australia, Email: patrick.berry@uts.edu.au*
*2 School of Computer Science, FEIT, University of Technology Sydney, Australia, Email: madhushi.bandara@uts.edu.au*

**Abstract:** This study plans to verify the benefits of integrating Knowledge Graphs with Intelligent Digital Twins for the management of complex man-made systems through simulation. Complex systems contain large numbers of interacting parts which are difficult to fully understand and control. Examples of complex natural systems include the human body, an ecosystem, or the atmosphere. Examples of complex man-made systems include critical infrastructure such as rail, electricity, telecommunications, and water networks. Digital Twins and Digital Twins augmented with Knowledge Graphs have been proposed as tools to assist the operators of complex systems to better manage the operations of these systems under both normal and upset conditions. This study seeks to verify the benefit of Digital Twins and Digital Twins augmented with Knowledge Graphs (Intelligent Digital Twins, iDT) using simulation and the Design Science Research (DSR) methodology. The DSR methodology is well suited to this area of study as it is a problem-solving methodology that seeks to enhance human knowledge through the creation of useful artifacts.

**Keywords:** digital twin; complex network systems; knowledge graphs; industry 4.0; design science research; intelligent digital twins

***Corresponding author:** Patrick Berry, Faculty of Engineering and IT, University of Technology Sydney, Australia. Email: Patrick.berry@uts.edu.au

## 1. Introduction

The world is made up of many complex natural and man-made systems. Complex systems contain large numbers of interacting parts which are difficult to fully understand and control. Examples of complex natural systems include the human body, an ecosystem, or the atmosphere. Examples of complex man-made systems include critical infrastructure, such as rail, electricity, telecommunications, and water networks; automated manufacturing facilities found in the automotive, petrochemical, food and beverage, and consumer goods industries. Many infrastructure and manufacturing systems can be represented as complex networked systems (CSN). Some examples include power networks, water distribution and collection networks, and complex chemical process plants. The physical assets of critical infrastructure (water, energy, transport, etc.) and manufacturing have been digitally controlled since the mid-1970s.

Industry 4.0 refers to the current phase of increasing levels of industrial automation which utilize modern standards-based ICT technologies to tightly couple enterprise IT systems and traditional industrial automation to improve efficiency, time-to-market, reduce waste etc. AI and ML techniques are some of the key new technologies driving Industry 4.0. Digital Twins have been proposed as a tool to aid in understanding complex systems. Digital Twins can also provide decision support to operators of complex infrastructure and industrial systems.

The concept of Digital Twins (DTs) was first introduced by (Grieves, 2015) in the Product Lifecycle Management (PLM) course in 2003 at the University of Michigan. A digital twin is a virtual replica (or model) of a physical object or system which is linked, enabling the model to be dynamically updated based on the state of the physical object or system.

The definition of Digital Twins will be expanded in the following section; however, it should be noted that even though Digital Twins have been discussed in the literature for close to 20 years, there remains a lack of a consensus definition of the term. "Academia and industry alike have not helped in distinguishing DTs from general computing models and simulations. Future work requires a more definitive definition for a Digital Twin." (Fuller et al., 2020). More recently Grieves has expanded the concept of the Digital Twin to incorporate AI and ML in Intelligent Digital Twin (Grieves, 2022).

Several authors have proposed that Knowledge Graphs be used to enhance Intelligent Digital Twins (Grangel-González et al., 2018; Sahlab et al., 2021; Steinmetz et al., 2022). While there have been many papers proposing the use of Knowledge Graphs to augment Intelligent Digital Twins, there have not been many experimental results verifying that the concept even works let alone how useful it is (Fuller et al., 2020).

This paper describes research in progress which plans to utilize complex network modelling and knowledge graphs to represent complex systems associated with Industry 4.0 and digital twins. This work will aim to demonstrate that Digital Twins augmented with Knowledge Graphs will allow operators of complex infrastructure and industrial systems to improve operating efficiency and effectiveness.

## 2. Background and Literature Review

The term Digital Twin was first introduced in 2015 (Grieves, 2015) and has been an active area of research since that time, however the term is still relatively ill defined. Two recent comprehensive reviews (Jones et al., 2020; Semeraro et al., 2021) have attempted to define the consensus requirements for a Digital Twin, this includes,

- A physical object or system
- A virtual representation of the object or system (These models were originally physics based. More recently this has been expanded to include ML and AI models.)
- An evolving set of data relating to the object or system.
- A dynamic link between the physical and virtual representation

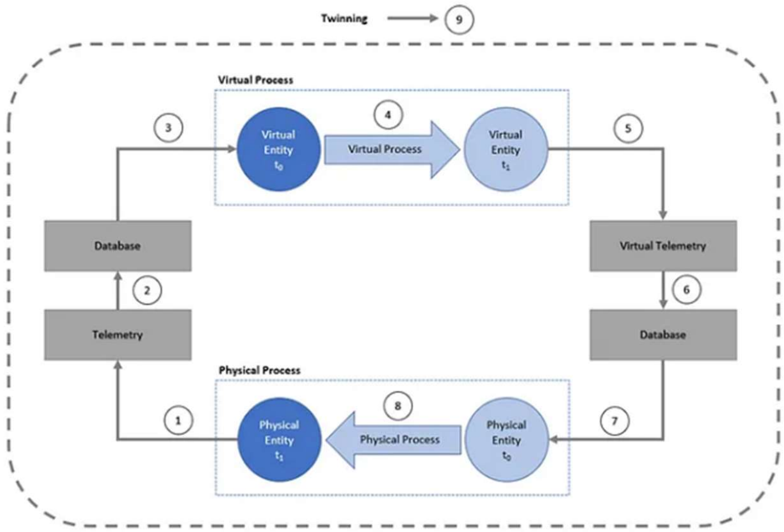
In addition to the above requirements, a common additional requirement is a mechanism for the virtual representation to update the physical representation (It could be argued that if this is not in place, then the Digital Twin concept has little value).

After reviewing over 150 papers, Semeraro et al. (Semeraro et al., 2021) offer the following working definition of a Digital Twin,

*A set of adaptive models that emulate the behaviour of a physical system in a virtual system getting real time data to update itself along its life cycle. The digital twin replicates the physical system to predict failures and opportunities for changes, to prescribe real time actions for optimizing and/or mitigating unexpected events observing and evaluating the operating profile system.*

Figure 1, below represents the relationship between the digital and physical entities, including the information flows, this is based on the work of Jones et al. (Jones et al., 2020)

**Figure 1**
**Representation of a Digital Twin, produced by (Berry, 2022) based on (Jones et al., 2020, fig. 7)**

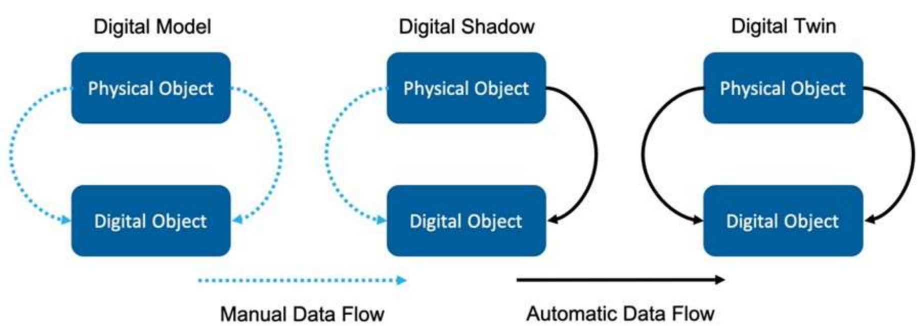



## 2.1 Benefits and Applications of Digital Twins

Digital Twins can be applied to individual products, complex assets, buildings as well as systems and processes, and systems of systems (Grieves, 2015). It should be noted that Digital Twins do not only apply to man-made systems, but they are also equally applicable to biological and environmental systems.

As noted above, a consensus definition of Digital Twins has not yet been reached. Both Digital Models and Digital Shadows are often incorrectly labelled as Digital Twins. Figure 2 below, depicts the difference between a Digital Model, Shadow and Twin based on information flows.

**Figure 2**
**Comparison of Digital Model, Shadow, and Twins. Source: (Fuller et al., 2020, fig. 1)**

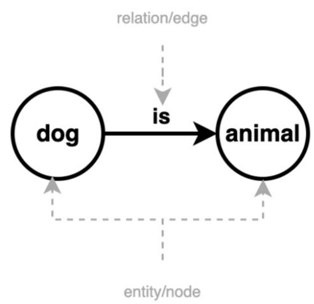



While various implementation architectures for Intelligent Digital Twins have been proposed (Ashtari Talkhestani et al., 2019). A significant gap exists in the literature with many Digital Twin architectures proposed, few proof-of-concept implementation and limited large-scale implementations. Fuller et al. observes that, “Manufacturing and fully integrated Digital Twins are proposed in the literature but are not currently realized in industry”. (Fuller et al., 2020).

## 2.2 Knowledge Graph Augmentation of Digital Twins

Knowledge Graphs have been proposed by various authors (Banerjee et al., 2017; Muller et al., 2022; Sahlab et al., 2021; Yahya et al., 2021) as an augmentation to Digital Twins. Knowledge Graphs store data as a collection of entities (graph nodes) and relationships between entities (graph edges). The entities and relationships can also store attribute data, this is depicted in Figure 3 below.

**Figure 3**
**Knowledge Graph Example. Source (Steinmetz et al., 2022, fig. 1)**




Knowledge Graphs are highly suited to apply to Digital Twins of complex systems as complex systems are composed of a large number of entities with complex relationships. Graph databases generally support graph query languages such as Cypher and SPARQL which enables complex graph queries to be constructed and executed by the database.

Several examples of augmentation of Digital Twins with Knowledge Graphs exist in the literature. One proposed implementation is to create custom nodes for Node-RED (Steinmetz et al., 2022; Thuluva et al., 2020). The work by Thuluva generates a W3C WoT description for the digital twin model. Steinmetz approach is to generate a graph in a Neo4j database.

Steinmetz provides an implementation of a Digital Twin model for an industrial valve (a relatively small component of an industrial process plant, an oil refinery in this case). The use case presented demonstrates that the Node-RED components developed were able to model a simple system including producing a knowledge graph representation. Two things that were not demonstrated were, the operational benefit of having a knowledge graph augmented digital twin and how the approach scaled to larger systems which would typically be found in industry.

## 3. Proposed Method

This study will attempt to verify the benefits of Knowledge Graph augmented Digital Twins on the management of complex man-made system through simulation.

The proposed methodology for this project is to conduct experiments to determine if a specific scenario on a physical asset can be detected using a digital twin that would provide useful insights to the operator of a complex system. This will entail,

1. Simulate a Physical System: Create a simulation of a small industrial process and include the ability to generate faults (failed equipment, incorrect sensor readings, changes in equipment health) or other scenarios corresponding to the identified use cases to be tested.
2. Build a Digital Twin: Create a Digital Twin corresponding to the simulated physical asset and link.
3. Conduct Experiments: Conduct experiments on the simulated physical asset and the Digital Twin to test if the identified scenarios for each use case can be detected.

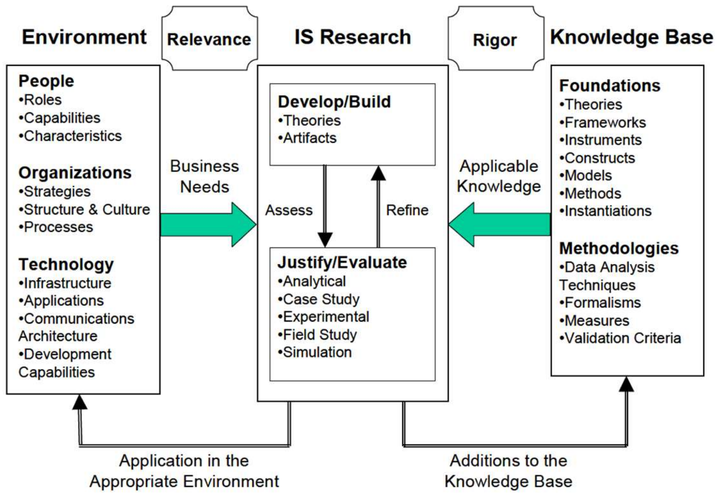
The hypothesis that is planned to be tested in this study is that Knowledge Graph augmented Intelligent Digital Twins are able to support operators of complex man-made systems allowing them to make better operational decisions, improving utilization, efficiency and decreasing operating costs.

The research approach chosen for this study is Design Science Research (DSR). "Design Science Research (DSR) is a problem-solving paradigm that seeks to enhance human knowledge via the creation of innovative artifacts." (Vom Brocke et al., 2020). DSR is especially suited to dealing with artificial (as in man-made) domains. As Digital Twins are either partially or fully artificial creations, they are well suited to the DSR method.

When Hevner et al. first introduced the Design Science research methodology for Information Systems research (A. R. Hevner et al., 2004) they presented a framework and a set of seven principles for implementation.

The diagram presented in Figure 5- Information Systems Research Framework, (A. R. Hevner et al., 2004, fig. 2) presents the DSR research framework (for Information Systems). This work was later expanded (A. Hevner & Chatterjee, 2010) to include a number if research cycles in the process related to relevance, design, and rigor.

**Figure 5**
**Information Systems Research Framework, (A. R. Hevner et al., 2004, fig. 2)**




This project seeks to confirm if Knowledge Graphs can be used to augment Digital Twins and if these Knowledge Graph Augmented Digital Twins are able to support operators of complex man-made systems. The focus of DSR is the creation of new knowledge through the creation of new artifacts (processes, products, etc.) and evaluating the utility of these artifacts in practice. Using the DSR method will enable the project's research question to be evaluated, by proposing a number of potential design solutions (artifacts), building, and then testing these artifacts to prove our hypotheses.

## 4. Planned Implementation and Evaluation

Planning of this study has utilized the DSR Grid approach which was proposed by (Vom Brocke & Maedche, 2019). The DSR grid attempts to summarize a DSR project using six key dimensions: Problem, Research Process, Solution, Input Knowledge, Concepts, Output Knowledge. The table below is a summary of the proposed implementation methodology.

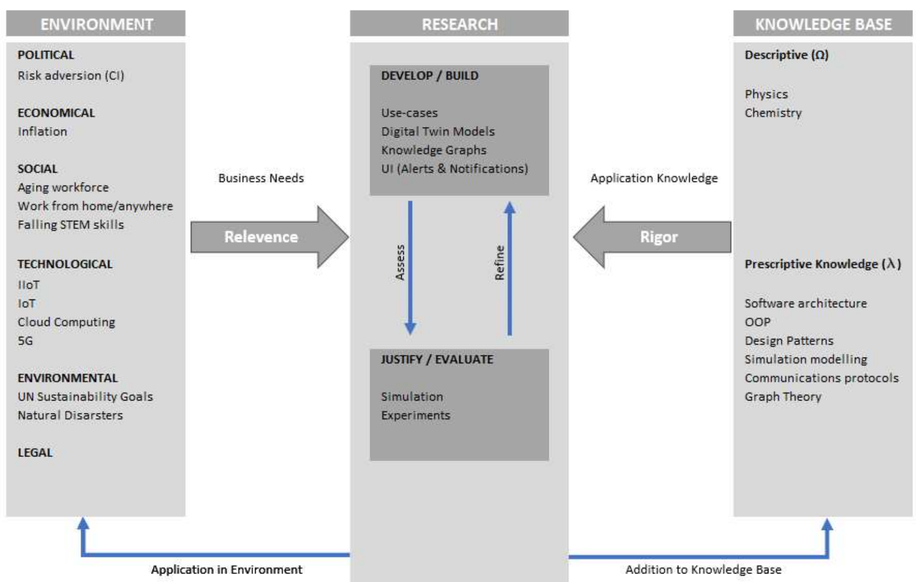
**Table 1**
**Completed DSR Grid for the study, based on (Vom Brocke & Maedche, 2019, fig. 2)**

| PROBLEM | RESEARCH PROCESS | SOLUTION |
|---|---|---|
| Complex man-made systems are difficult to manage due to the large number of interacting components. The large number of components and their dependencies make it difficult for the operators to diagnose the root cause of failures, assess the impact of proposed changes due to maintenance or upgrades, understand the current health of the system and to manage ongoing performance. | ***Problem identification:*** Primarily through review of case studies and the authors' own industry experience (potentially be augmented with workshops and/or surveys of industry)<br><br>***Iterative Design, Implement & Evaluate:*** Develop solution artifacts for identified problems, build, and evaluate.<br><br>***Final Evaluation:*** Review and evaluate all artifacts collectively and the conclusion of the project. | A framework to apply Knowledge Graphs to Digital Twins.<br>A set of use cases to demonstrate how the framework is applied that beings benefit to the operators of complex man-made systems. |

| INPUT KNOWLEDGE | CONCEPTS | OUTPUT KNOWLEDGE |
|---|---|---|
| Digital Twins have been successfully applied in some industries and have the potential to assist in the management complex man-made systems.<br><br>The Digital Twin concept has been expanded to Intelligent Digital Twins (iDT) with the integration of ML and AI.<br><br>Knowledge Graphs have been shown to be able to represent semantic knowledge in DT models. | Digital Twin<br>Intelligent Digital Twin<br>Knowledge Graph<br>Simulation & Modelling<br>Computational Science | A set of validated design patterns for solving use-cases which have shown to be of benefit to operators of complex man-made systems. |

The DSR framework has been previously mapped to the IT domain by Hevner et al. (A. R. Hevner et al., 2004, fig. 2). In Figure 6 below, we show how their framework has been adopted to this research project (the application of Digital Twins). To populate the Environment domain, the well-known PESTEL methodology (Child, n.d.) has been used.

**Figure 6**
**DSR Framework adapted for this research, based on (A. R. Hevner et al., 2004, fig. 2)**

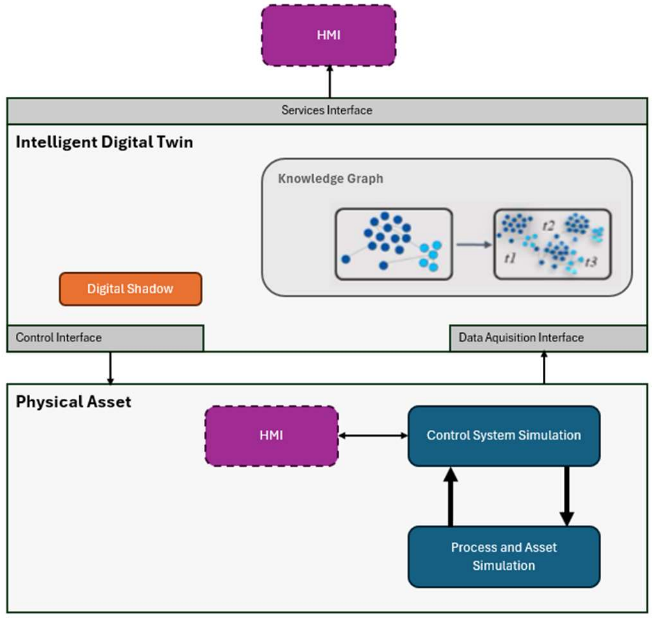



This study will include two distinct phases of experimental work. The first will be to create an environment in which DSR experiments can be run, the second will be to create DSR artifacts and run experiments on those artifacts. The experimentation environment will contain:

- An environment for running simulations of Physical Object(s).
- An environment for creating and running Digital Objects(s).
- A mechanism to transfer data from the Physical to the Digital Objects.
- Various components that may be required to augment the Digital Object (time series databases, graph databases, visualization tools etc.)

Below is a conceptual depiction of the proposed experimental environment.

**Figure 7**
**Conceptual Model of Experimental Environment**




## 5. Discussion and Conclusion

Digital Twins augmented with Knowledge Graphs have the potential to allow operators of complex infrastructure and industrial systems to improve operating efficiency and effectiveness. This has the potential to have both economic and environmental benefits. While the benefits of Digital Twin technology have been proposed for some time, outside of selected industries, little benefit has been realized in practice.

The DSR methodology, with its focus on the artificial and the creation of artifacts, is well suited to the exploration of the benefits of the application of Digital Twins to complex processes.

The next phase of this study will be the development of the experimental environment in which DSR experiments can be conducted.

This research project has several potential avenues for future work would which are briefly described below,

**Close the Loop and Make a True DT.** According to (Fuller et al., 2020), the experiments proposed in this study would constitute a Digital Shadow rather than a Digital Twin. Future work could include closing the link from virtual representation to physical entity, where the recommendations made by the operator decision support system are automatically applied to the physical system.

**Additional Enhancements to the iDT.** Knowledge Graphs are one proposed augmentation to Intelligent Digital Twins. Future work could include exploring other ML and AI techniques as iDT enhancements as well as the application of ML to the Knowledge Graph.

**Trial on Real System/Data.** The methodology used in this project is to simulate the physical entity. Future work could include alloying the experimental results to a real-world asset or system.

**Automatic Model Creation from P&ID and Other Design Documents.** Creation of Digital Twin models is currently extremely labor intensive. Future work could include the automated or semi-automated development of models existing design artifacts. This could include Process and Instrumentation Diagrams, asset databases, etc.

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## Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

## Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

## Data Availability Statement

Not applicable.

## References

Ashtari Talkhestani, B., Jung, T., Lindemann, B., Sahlab, N., Jazdi, N., Schloegl, W., & Weyrich, M. (2019). An architecture of an Intelligent Digital Twin in a Cyber-Physical Production System. At - Automatisierungstechnik, 67(9), 762–782. https://doi.org/10.1515/auto-2019-0039

Banerjee, A., Dalal, R., Mittal, S., & Joshi, K. P. (2017). Generating Digital Twin Models using Knowledge Graphs for Industrial Production Lines. Proceedings of the 2017 ACM on Web Science Conference, 425–430. https://doi.org/10.1145/3091478.3162383

Berry, P. (2022, February 3). What is (and what isn't) a Digital Twin. Industrial Digital Transformation & Industry 4.0 | Medium. https://medium.com/industrial-digital-transformation-industry-4-0/what-is-and-what-isnt-a-digital-twin-9880fc87abc3

Child, J. (n.d.). Subject guides: Marketing: PESTLE Analysis. Retrieved 7 November 2023, from https://libguides.library.usyd.edu.au/c.php?g=508107&p=5994242

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access, 8, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

Grangel-González, I., Halilaj, L., Vidal, M.-E., Rana, O., Lohmann, S., Auer, S., & Müller, A. W. (2018). Knowledge Graphs for Semantically Integrating Cyber-Physical Systems. In S. Hartmann, H. Ma, A. Hameurlain, G. Pernul, & R. R. Wagner (Eds.), Database and Expert Systems Applications (Vol. 11029, pp. 184–199). Springer International Publishing. https://doi.org/10.1007/978-3-319-98809-2_12

Grieves, M. (2015). Digital Twin: Manufacturing Excellence through Virtual Factory Replication.

Grieves, M. (2022). Intelligent digital twins and the development and management of complex systems. Digital Twin, 2, 8. https://doi.org/10.12688/digitaltwin.17574.1

Hevner, A., & Chatterjee, S. (2010). Design Science Research in Information Systems. In A. Hevner & S. Chatterjee, Design Research in Information Systems (Vol. 22, pp. 9–22). Springer US. https://doi.org/10.1007/978-1-4419-5653-8_2

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design Science in Information Systems Research. MIS Quarterly, Vol. 28 No. 1, 75–105.

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology, 29, 36–52. https://doi.org/10.1016/j.cirpj.2020.02.002

Muller, T., Sahlab, N., Kamm, S., Kohler, C., Braun, D., Jazdi, N., & Weyrich, M. (2022). Context-enriched modeling using Knowledge Graphs for intelligent Digital Twins of Production Systems. 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA), 1–8. https://doi.org/10.1109/ETFA52439.2022.9921615

Offermann, P., Levina, O., Schönherr, M., & Bub, U. (2009). Outline of a design science research process. Proceedings of the 4th International Conference on Design Science Research in Information Systems and Technology - DESRIST '09, 1. https://doi.org/10.1145/1555619.1555629

Reiche, F., & Timinger, H. (2021). Process Model for Integrated Product Lifecycles Using Digital Twins and Predictive Analytics. 2021 IEEE Technology & Engineering Management Conference - Europe (TEMSCON-EUR), 1–5. https://doi.org/10.1109/TEMSCON-EUR52034.2021.9488653

Sahlab, N., Kamm, S., Muller, T., Jazdi, N., & Weyrich, M. (2021). Knowledge Graphs as Enhancers of Intelligent Digital Twins. 2021 4th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS), 19–24. https://doi.org/10.1109/ICPS49255.2021.9468219

Semeraro, C., Lezoche, M., Panetto, H., & Dassisti, M. (2021). Digital twin paradigm: A systematic literature review. Computers in Industry, 130, 103469. https://doi.org/10.1016/j.compind.2021.103469

Simon, H. A. (1996). The sciences of the artificial (3rd ed). MIT Press.

Stappers, P. J. (2007). Doing Design as a Part of Doing Research. In R. Michel (Ed.), Design Research Now (pp. 81–91). DE GRUYTER. https://doi.org/10.1007/978-3-7643-8472-2_6

Steinmetz, C., Schroeder, G. N., Sulak, A., Tuna, K., Binotto, A., Rettberg, A., & Pereira, C. E. (2022). A methodology for creating semantic digital twin models supported by knowledge graphs. 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA), 1–7. https://doi.org/10.1109/ETFA52439.2022.9921499

Stokes, D. E. (1997). Pasteur's quadrant: Basic science and technological innovation. Brookings Institution Press.

Thuluva, A. S., Anicic, D., Rudolph, S., & Adikari, M. (2020). Semantic Node-RED for rapid development of interoperable industrial IoT applications. Semantic Web, 11(6), 949–975. https://doi.org/10.3233/SW-200405

Vom Brocke, J., Hevner, A., & Maedche, A. (2020). Introduction to Design Science Research. In J. Vom Brocke, A. Hevner, & A. Maedche (Eds.), Design Science Research. Cases (pp. 1–13). Springer International Publishing. https://doi.org/10.1007/978-3-030-46781-4_1

Vom Brocke, J., & Maedche, A. (2019). The DSR grid: Six core dimensions for effectively planning and communicating design science research projects. Electronic Markets, 29(3), 379–385. https://doi.org/10.1007/s12525-019-00358-7

Yahya, M., Breslin, J. G., & Ali, M. I. (2021). Semantic Web and Knowledge Graphs for Industry 4.0. Applied Sciences, 11(11), 5110. https://doi.org/10.3390/app11115110