TOWARDS A TAXONOMY OF BUILT ASSET LIFECYCLE INFORMATION COUPLING

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Abstract

The accelerating pace of digitalization of the built asset industry is pushing towards a tighter coupling of digital and physical assets and resources. Such coupling shows promise in allowing industry stakeholders to unlock the value generated through integrated information management and processing across an asset's lifecycle. Within the context of cyber-physical systems in the Built Environment, a growing number of studies are focusing on the application of Digital Twins (DT)s, in which a digital model reflects the state of a physical asset at any given moment. As a nascent field of study, the concepts and terminology used to describe, study, and develop the domain are still evolving. In many cases, several of these concepts must be coined and defined to act as a foundation to support the development and instantiation of theories, models, and frameworks applicable within this domain. This paper proposes a taxonomy of Built Asset Lifecycle Information Couples which provides the core elements, definitions and characteristics framing the physical-digital coupling of assets and resources in the built asset industry. The proposed taxonomy developed in this paper contributes to the effort aimed at structuring the knowledge domain of lifecycle information management through the coupling of physical and digital worlds in the built environment.

Keywords: Asset Coupling, Taxonomy, Digitalization, Digital Representation, Lifecycle Management.

1 Introduction

The past decade has seen the rapid digitalization of the built asset industry which provides opportunities for considerable gains in terms of performance and value generation through optimization. This digitalization is manifested through the coupling of digital and physical built assets and has been demonstrated through recent studies on Cyber-Physical Systems (CPS) and Digital Twins (DT) applied to the built environment (Macchi et al 2018). Although the benefits are becoming evident, there is still a need to better define and frame the core principles and components of lifecycle information coupling in the built environment.

While the body of knowledge pertaining to the technical aspects of CPS and DT is growing, there still lacks a common basis of terms, definitions, concepts, and dimensions pertaining to lifecycle information coupling. Taking full advantage of this concept in the built asset industry requires new constructs – taxonomies, models, and frameworks - to define and put into relation the many components which comprise the coupling of physical and digital of assets and resources in the built environment across lifecycle phases. This encompasses elements such as the states and statuses, purposes, outcomes, types, levels, links, actions, metrics, and enablers that serve to characterize and define the *coupling* between physical assets and resources and their digital counterparts as well as their coupling across different lifecycle phases.

The work set out in this paper addresses the current gap in the extant literature on coupling by provided the impetus for a common ground. It builds on the *Lifecycle Information Transformation and Exchange* (LITE) framework, "an extendable conceptual skeletal for defining, managing, and integrating project and asset information across its lifecycle [that] provides the foundation for a new information management paradigm, which supports emerging technologies and practices aiming towards integration and automation" (Succar & Poirier 2020, p.1). The work investigates and expands on key constructs of the LITE framework and focalises on the notion of built asset lifecycle information coupling. It proposes a taxonomy to initiate the structuring of the knowledge domain.

The paper first provides a background on the notion of representation in the context of lifecycle information coupling to identify the state-of-the-art and related works. It then exposes the need for a taxonomy by providing context and background on the LITE framework. Finally, the proposed Lifecycle Information Coupling taxonomy is offered as a foundation for future studies and implementations in this field of research.

2 Background Research

2.1 Representation theory and the coupling of the physical and the digital

The digitalization of built assets is associated with different forms of physical and digital representations to allow a dialogue between digital assets and their physical counterparts. According to Peirce's (1932) representation taxonomy, the nature of representations that have physical referents can be distinguished based on *indices*, *icons*, and *symbols*. Indices can mirror the behavior of a physical asset. Icons resemble a physical asset through visualizations (Bailey et al 2012). In contrast, symbols are decoupled from the physical domain and emphasize simulation and predictions (Østerlie & Monterio 2020). Symbols simulate a physical asset in an indirect manner, enabling the *tight coupling* between physical and digital assets. Leonardi (2012) defined "*tight coupling*" in the simulation process as the state in which representations are highly dependent on physical referents. On the other hand, the term "*decoupling*" refers to further distance or independency between representation and its physical referents.

While representation of physical and digital objects, processes, and qualities has been theorized based on different types of virtual works (Bailey et al 2012), the challenge is to define precisely how digital can be made real as physical and digital assets become increasingly coupled (Østerlie & Monterio 2020). While some proponents oppose theorizing representational boundaries, arguing that representation theory should be tailored to specific applications and circumstances (Burton-Jones & Grange 2013), others embrace the plurality and permeability of the physical and the digital, the real and the unreal. For instance, Boellstorff et al (2016) introduce the "*digital reality matrix"* (Figure 2.1) in which different forms of realities and unrealities are articulated across physical and digital states. While such work provides a workable starting point, more targeted investigation into the materialization and dematerialization of the physical and the digital is warranted. Indeed, rethinking the boundaries between – what is perceived as - *reality* and *unreality* would encourage a more diverse range of insights for increasing the coupling of the digital with the real, and the physical with the unreal in specific contexts.

As another approach to representational theory, Burton-Jones & Grange (2013) adapted information systems (IS) to connect the level of trust in digital artefacts with the accuracy in representation of real-world domains. The authors argued that the integration of "*representation fidelity*" and "*transparent interaction*" enables more effective use of the system. The terms "*representation fidelity*" and "*transparent interaction*" here characterize the *extent* to which representations are faithful, and the heightened level of accessibility of users to the deeper structure of a system (system-provided representation). As physical and digital assets become increasingly coupled, these two dimensions of representation can be applied – both conceptually and functionally - to measure the effectiveness of information coupling between physical structures and their digital representations.

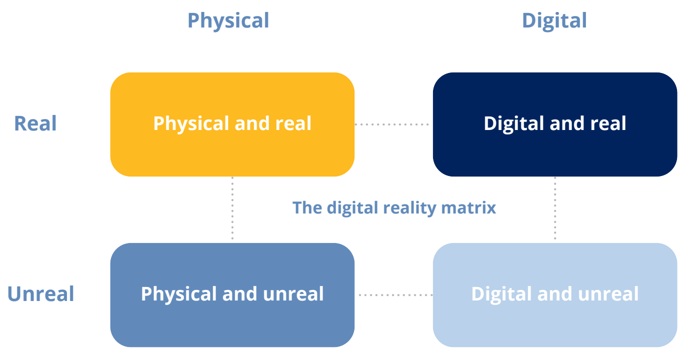

Figure 2.1. The digital reality matrix – adapted from Boellstroff et al (2016)

Many scholars and practitioners, from various knowledge and industrial domains, have commonly argued for effective mechanisms to increase the tight coupling between digital representation and physical assets. For example, Østerlie & Monterio (2020) conducted an empirical study on off-shore oil production and identified three mechanisms to translate digital representation into operationalizable knowledge: (1) through data aggregation in which irrelevant data and signals are filtered to identify the most reliable and desired sensor data; (2) signal coupling in which the digital representation is coupled to their physical counterparts; and (3) modeling through which digital representations are created, the materialization of data into knowledge serves to support the organization in its day-to-day operations. Similar mechanisms were observed by Yoo et al (2010) who investigated Frank Gehry's design process, where architectural teams used simulations to maintain the tight coupling between digital representation and physical counterparts.

From a technical standpoint, the integration of multi-disciplinary representation models across lifecycle phases of an asset remains challenging (Talkhestani et al 2019). This is in part due to the high levels of correlation and calibration that are required to allow the incorporation of multi-disciplinary models and their ongoing use at various phases of an asset's lifecycle. In addition, the usefulness of any digital representation depends on the capacity of digital tools to collect and synchronize data and their representation across physical and digital assets.

Many enabling technologies have been identified in order to ensure reliable data collection and transformation within built assets. However, as large amounts of data are produced and shared between physical components and digital models, a number of issues become more critical (Wang et al 2019). Also, a significant portion of collected data may be unreliable signals, noise that must be filtered prior to information coupling between physical and digital assets and resources (Østerlie & Monterio 2020). As such, the lack of qualified sensors and monitoring systems that serve to actively filter irrelevant data collected from physical sources require constant validation to verify what data has been exchanged with which system and how the filtering measures have been implemented to ensure quality and consistency of data and its representation (Reeves & Maple 2019). Current limitations noted, the past decade has seen a rapid acceleration and increasing diffusion of enabling technologies that can support coupling of physical and digital assets.

2.2 Lifecycle information coupling across domains

The concept of asset and information coupling is a potential enabler of better project and asset performance by providing enhanced decision support and insight across the lifecycle of built assets. Although the concept of asset and information coupling has been explored in the context of Cyber-physical systems (CPS), principles and characteristics of asset and information coupling has received less attention in the built asset domain.

According to BIM Dictionary (2021), asset coupling means "*development and/or maintenance of digital assets so they accurately match the physical Assets they represent*". Asset coupling allows any changes in one asset to be reflected in its counterpart. The term "Asset" here refers to any physical or digital entity such as buildings, equipment, materials, etc. (Succar & Poirier 2020). De Roure et al (2019) described "*lifecycle coupling*" as an interaction between physical assets (e.g.

physical devices in the infrastructure of a built asset) with other digital systems sustained across time. Effective information flow and exchange throughout an asset's lifecycle (e.g. from planning to disposal) is the most important aspect of the coupling process which enables progress monitoring and real-time decision making (Boje et al 2020).

Being able to *predict* and *optimize* the state of physical and digital assets is a common requirement for asset coupling. Some studies have proposed the creation of a "predictive couple", which is a physics-based couple that receives real-time data and exploits it as a pattern to predict the behaviour of assets throughout of their lifecycle phases (Oracle 2019). Following this, a mechanism such as a "couple projection" can be devised to incorporate predictions into actual organizational workflows to facilitate predictability of physical and digital assets and resources. Again, as with representation, enabling lifecycle information coupling requires effective data acquisition with a high level of fidelity and trustworthiness (Reeves & Maple 2019). A considerable amount of work has been performed in this area. For instance, Akanmu & Anumba (2015) compiled a list of potential digital information tools for data collection and exchange between physical and digital assets. However, only a few years later, the list already needs to be expanded due to increasing demand and availability of automated and autonomous information coupling technologies. Across domains, the implementation of IoT technologies and Big Data concepts reveal great potential towards improving the performance and capacity of models acting as the digital couple. Other studies have suggested that to cope effectively with the proliferation and capabilities of IoT, coupling processed need to be facilitated by Artificial Intelligence (AI) methodologies so to accelerate data processing, accuracy, and reliability (El Sadidik 2018).

2.3 The LITE framework and information lifecycle couples

In our previous publication, the authors have suggested that the digitalization of built asset lifecycle information and its integrated management require a digital platform connecting the design, delivery, and utilisation of built assets. The development of such a platform – as both a expandable conceptual construct and an open access online solution – will unlock numerous possibilities to demonstrate the efficient coupling of physical and digital assets and resources across their lifecycles. This paper builds upon the modular components of the *Lifecycle Information Transformation and Exchange* (LITE) framework (Succar and Poirier, 2020) to deliver a *lifecycle information coupling* taxonomy. Through closed and open loops, the LITE framework allows information to circulate and evolve according to specific routes and across distinct milestones, starting with the intent to deliver an asset through to its realization and subsequent intent to reuse or recycle. The modular information components of the framework provide the flexibility to represent different asset types, functions, and scales. Focusing on asset scale, the framework allows representation of assets at different granularity levels: from a single functional part of the building (e.g. controller box) to a portfolio of many larger or smaller sub-assets (e.g. a site or a whole city) are considered and covered. Furthermore, the framework enables information to transform automatically and autonomously between information milestones, something rarely supported in the extant literature. This flexibility is well-suited to support benefitting for emergent applications of machine learning and asset tokenisation through distributed ledger technologies. The LITE framework also provides a rational through which information flows can be understood, explained, and predicted.

The LITE framework develops specific conceptual constructs and articulates them within a model. For instance, and regardless of their scale, asserts are either *targeted* or *actualized* as intimated by the digital reality matrix. They can exist in either their physical or digital forms (or both) and these assets can be coupled and interact in many ways. Information flows in LITE framework can be aggregated and integrated across eight information millstones and, throughout the information lifecycle, the information can be integrated within a unified pool of overlapping information sets. Of interest in the context of this paper are the six information-milestone couples, with each couple relating to a specific aspect of the information lifecycle and serving to bridge two specific divides: between physical and digital worlds or between targeted (unreal) and actual (real) states. As shown in Figure 3.1, Milestone Couples reflect the information statuses and states within the framework. The *targeted* and *actual* information statuses are linked by four *vertical*

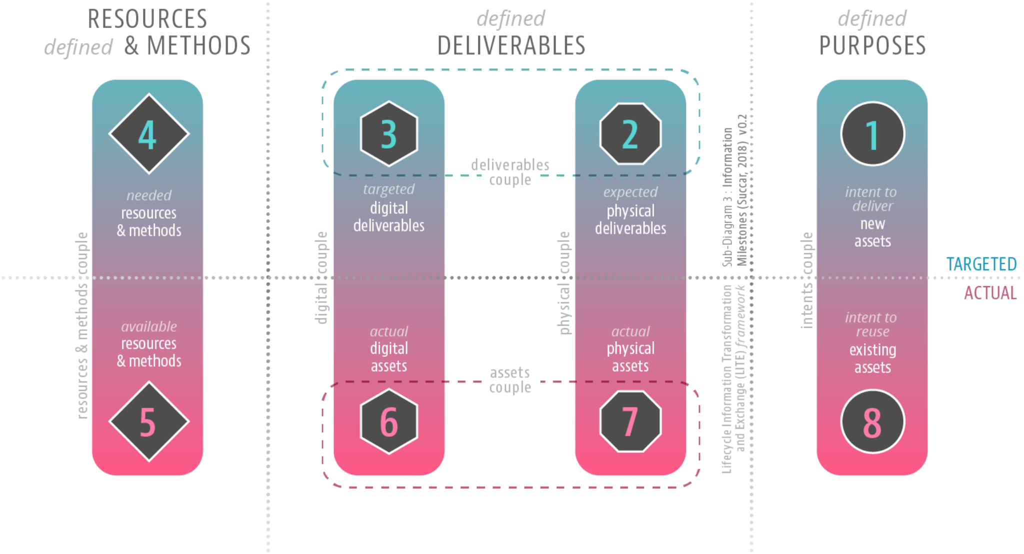

Figure 3.1. LITE framework (*Information Milestones and their couples*) – Succar & Poirier (2020)

couples: Purposes Couple, Physical Couple, Digital Couple, and Resources and Method Couple. To ensure constant synchronization between targeted and *actual* deliverables, two *horizontal couples*: Deliverable Couple and Asset Couple are projected respectively. All these positioned couples can unlock new avenues to facilitate information coupling at different stages of the asset lifecycle. However, further explanations and definitions are necessary to define more granular coupling actions, metrics, and enablers for future technical implementations.

3 The Need for a Taxonomy

The models and frameworks discussed above have primarily focused on system architectures and information coupling applications. Based on reviewed literature, an increasing number of publications have proposed a taxonomy covering Digital Twins (DT)s and asset information management. For example, Van der Valk et al (2020) attempted a taxonomy to unify all definitions and elements of Digital Twins from published literature. It included eight dimensions and their corresponding characteristics that can be utilised and extended to provide a definitional understanding of Digital Twins. Similarly, and in response to ongoing trends toward the implementation of Blockchain for DTs, Yaqoob et al (2020) presented a taxonomy from DT literature. In their study, the taxonomy unified several key aspects of DTs, including design phases, industrial use cases/applications, and enabling technologies. These and similar taxonomies shed needed light on the patterns underpinning commonly used definitions of DTs within industry and academia. In contemplating these, the LITE framework highlights several gaps in common approaches to lifecycle information management and processing. The one deserving attention here is that Built Asset lifecycle information coupling should not be limited to Digital Twins of physical assets. As highlighted in figure 3.1, DTs represent only one of the six potential Built Asset Lifecycle Information Couples. These six types of couples deserve a more focused attention and will be well served through the development of a taxonomy that detail all built asset lifecycle information couples and their characteristics. This paper will initiate this effort and provide a foundation for this taxonomy and offer this taxonomy for continuous extension and refinement by domain researchers.

4 A Taxonomy for Built Asset Lifecycle Information Coupling

Representing the main types and characteristics of Built Asset Lifecycle information couples, Figure 4.1 depicts a proposed taxonomy with seven high-level components: *Information Couples, Coupling States, Coupling Purposes, Coupling Outcomes, Coupling Actions, Coupling Metrics,* and *Coupling Enablers*:

4.1 Information Couples

Coupling types refer to their position and purpose within the LITE framework. Six couples are developed as either *vertical* couples connecting what is *targeted* to what is *actual* across the lifecycle phases of an asset and *Horizontal couples* connecting digital assets and their physical counterparts, be they targeted or actualized.

Vertical couples can be used to validate or verify an asset's current state against its targeted state. For example, determining whether a deliverable model meets its intended purposes or not. Vertical couples reveal new possibilities for asset reconstruction, reuse, and recycling and include four couples: Purpose Couple, Physical Couple, Digital Couple, and Recourses and Methods Couples. These *vertical* Couples determine how well actual assets (e.g. available resources, physical/digital assets) achieve their predefined purposes (e.g. needed recourses, physical/digital deliverables).

There are also two types of *horizontal* couples: Deliverables Couples and Asset Couples which represent, enable, and measure the synchronization between targeted digital and physical *deliverables* (e.g. between what physical assets are targeted and how these are served by digital models and documents), and between actual digital and physical assets commonly referred to as Digital Twins (Succar & Poirier, 2020).

4.2 Coupling States

Coupling states represent the condition of a built asset lifecycle information couple. These couples can be *Coupled, Uncoupled,* and *Recoupled.* Each state can indicate the condition of the coupling process between information milestones, including physical and digital assets and resources. This allows users to monitor if information milestones are coupled or not. For this case, *Active* couples may indicate "live" or dynamic couples whereas *Passive* couples denote milestone couples requiring specific triggers to instigate an action in a couple. In addition, the connection between assets and resources, digital or physical, can be coupled either in one-*direction* or *bi-directionally* (Van der Valk et al 2020). *Uni-directional* links are characterized by a *one-way* flow of information from one milestone to the other - for instance from actual physical assets to their actual digital counterparts. *Bi-directional* links are *two-way* flows of information that support both execution and measurement flows of information (Succar & Poirier, 2020). The coordination between physical and digital assets through Cyber Physical Systems are an example of this (Akanmu & Anumba 2015). In some circumstances, an asset or resource may be uncoupled temporarily – to do modifications - and then recoupled with required adjustments or synchronizations. *Active* couples may indicate "live" or dynamic couples whereas *Passive* couples denote milestone couples requiring specific triggers to instigate an action in a couple.

4.3 Coupling Purposes

Coupling purposes are the reasons guiding the development and implementation of a built asset lifecycle information couple. These purposes must be identified, from planning to maintenance phases of an asset. Amongst coupling purposes are *insights* (e.g. alternative production methods), *analysis* (e.g. structures, properties), *simulations* (e.g. modelling the behaviour of an object under load or kinetic force), and *predictions* (forecasting based on AI) can all support *decisions* (e.g. scheduling, business) to varying degrees.

4.4 Coupling Outcomes

Coupling outcomes are the expected effect of coupling actions for a specific purpose. These outcomes can be, among others, *value generation, quality* improvement, *sustainability*, *resilience* and *performance* of an asset or resource. Physical and digital assets may be coupled to achieve a specific value (e.g. the percentage of improvement in operation of an asset). The *performance* outcome represents the effectiveness of a coupling action in terms of functionality and efficiency of physical and digital assets.

4.5 Coupling Actions

Coupling actions are the methods and activities through which Lifecyle Information Couples are created and maintained. There are six principle coupling actions: *Acquire, Transmit, Model, Integrate, Consume,* and *Maintain.* Data and information can be acquired from either physical or digital sources, which are then *transmitted* to be *modeled* for specific purposes and outcomes (e.g. tools and equipment required to generate a project deliverable). Through *integration* actions additional inputs can be added to the models or representations. The *consume* action can be carried out based on the coupling purposes. Finally, the *maintain* action ensures a coupled asset's long-term serviceability and performance.

4.6 Coupling Metrics

Coupling metrics serve to support the measurement, assessment and evaluation of different dimensions relating to the performance, efficiency, or quality of an information couple. Several metrics of built asset lifecycle information coupling are identified as applicable for functional and representational couplings – these include: Coupling Level (Clevel) indicating the extent of connectedness (e.g. no coupling to high coupling/mirroring) between physical and digital built assets (BIM Dictionary 2021). The Level of Accuracy (LoA) is a measure of how accurate the couples are. Representation Fidelity (RF) refers to extent of faithfulness of a representation that is being used for coupling purposes. As representation Fidelity increases, users can trust representations more and use them for automatic decision making (Burton-Jones & Grange 2013). Within an information cycle, Degree of Automation (DoA) can be used to determine the extent of automation as physical and digital assets are coupled. As the Level of Accuracy increases, so may the Degree of Automation (Succar & Poirier 2020). Degree of Transparency measures the content accessibility of users to the coupling process, including structure of digital representations and their conceptual or physical counterparts (Burton-Jones & Grange 2013). Lastly, Asset Scale specifies the relative size of an asset for coupling purposes, ranging from a small part (e.g. door handle) to larger scales such as a country (e.g. region, province) or the entire world (e.g. planets; BIM Framework, 2019).

4.7 Coupling Enablers

Coupling enablers are the key technologies needed to operationalize theses lifecycle information couples. As such, coupling enablers have been divided into three categories: *Hardware*, *Network*, and *Software*. Potential technologies for each category have all been identified, including IoT devices, Artificial Intelligence (AI), Big Data, 5G network, BIM/CAD platforms, cloud computing, and haptics. There is a prevalence of work in this area whereby a layered architecture enabling the acquisition, transmission, integration and consumption of data and information is currently the predominant approach to enabling coupling in the context of DT (Lu et al. 2020). These enablers are evolving rapidly of course.

5 Conclusion

This paper reviewed the current state of physical and digital coupling through the lens of representation theories and lifecycle information management in the built asset industry. While existing frameworks and conceptual models are encouraging the tight coupling of physical and digital assets, a broader vision is adopted to understand key components and definitions that enable such couplings across lifecycle phases of a built asset. A taxonomy of Built Asset Lifecycle Information Coupling was proposed to identify the different characteristics guiding this trend towards the coupling of physical and digital assets and resources. This approach can serve to reduce the complexity of this evolving field of research. The main contribution of this proposed taxonomy is to enhance the understanding of information coupling in the built environment. However, further research is needed to develop and conceptualise other key aspects of lifecycle information coupling by extending and refining this taxonomy. As such, the next steps are to continue to develop the Built Asset Lifecycle Information Coupling taxonomy and generate more detailed principles, mechanisms, and information uses for dealing with the existing coupling issues in the lifecycle information management of built environment.

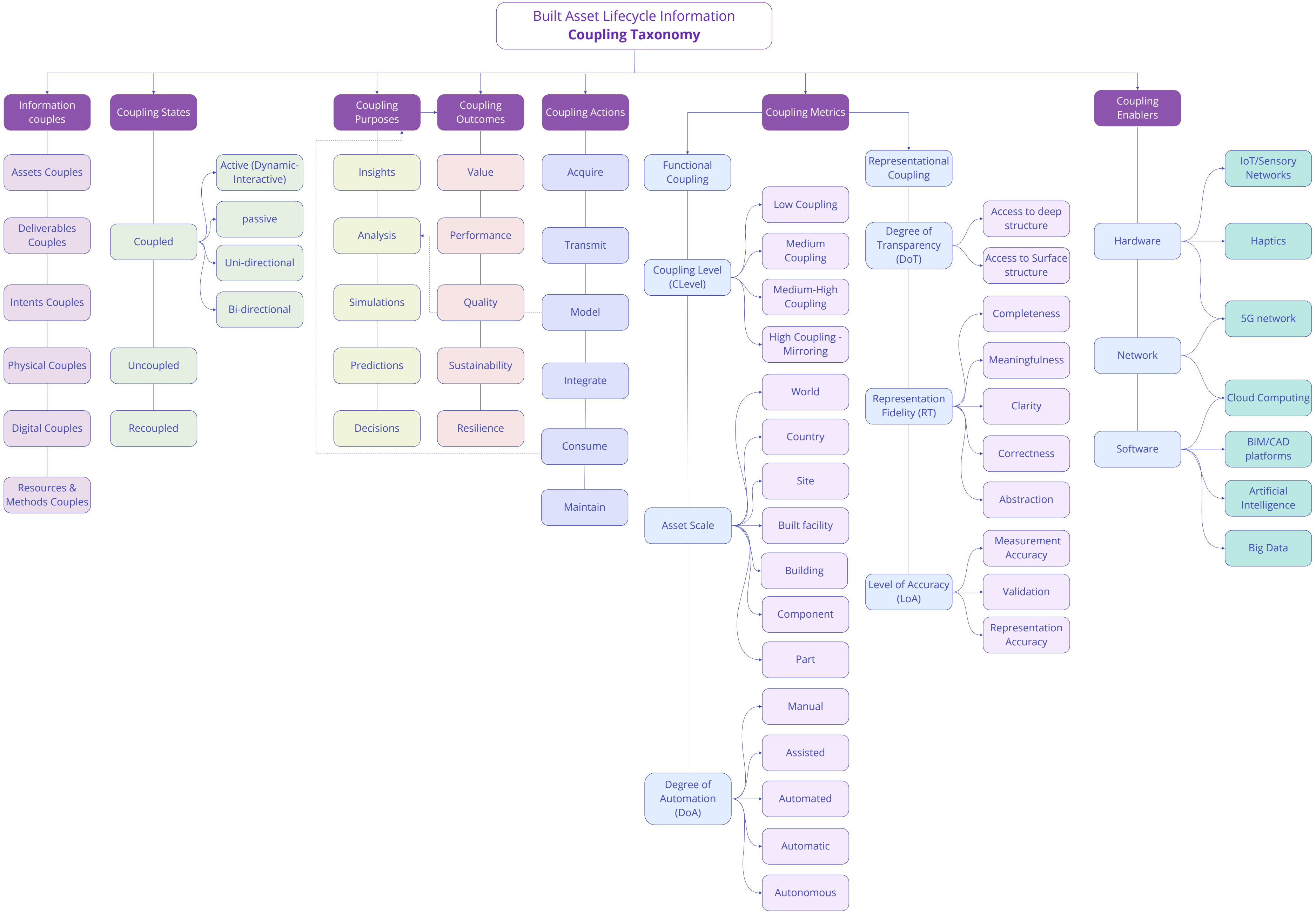

Figure 4.1. Built Asset Lifecycle Information Coupling Taxonomy – V1

References

Akanmu, A., & Anumba, C. J. (2015). Cyber-physical systems integration of building information models and the physical construction. Engineering, Construction and Architectural Management, 22(5), 516–535. https://doi.org/10.1108/ECAM-07-2014-0097

Alonso, R., Borras, M., Koppelaar, R. H. E. M., Lodigiani, A., Loscos, E., & Yöntem, E. (2019). SPHERE: BIM Digital Twin Platform. Proceedings, 20(1), 9. https://doi.org/10.3390/proceedings2019020009

Bailey, D. E., Leonardi, P. M., & Barley, S. R. (2011). The Lure of the Virtual. Organization Science, 23(5), 1485–1504. https://doi.org/10.1287/orsc.1110.0703

Boellstorff, T. (2016). For Whom the Ontology Turns: Theorizing the Digital Real. Current Anthropology, 57(4), 387–407. https://doi.org/10.1086/687362

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction, 114, 103179. https://doi.org/10.1016/j.autcon.2020.103179

Boy, G. A. (2020). Human–Systems Integration: From Virtual to Tangible. CRC Press. https://doi.org/10.1201/9780429351686

Burton-Jones, A., & Grange, C. (2012). From Use to Effective Use: A Representation Theory Perspective. Information Systems Research, 24(3), 632–658. https://doi.org/10.1287/isre.1120.0444

Cecconi, F.R., Dejaco, M.C., Moretti, N., Mannino, A. and Cadena, J.D.B., (2020). Digital asset management. In Digital Transformation of the Design, Construction and Management Processes of the Built Environment (pp. 243-253). Springer, Cham. https://doi.org/10.1007/978-3-030-33570-0_22

De Roure, D., Page, K.R., Radanliev, P. and Van Kleek, M., 2019. Complex coupling in cyber-physical systems and the threats of fake data. https://www.researchgate.net/publication/336341104

El Saddik, A. (2018). Digital Twins: The Convergence of Multimedia Technologies. IEEE MultiMedia, 25(2), 87– 92. https://doi.org/10.1109/MMUL.2018.023121167

Gelernter, D. (1993). Mirror Worlds: Or: The Day Software Puts the Universe in a Shoebox...How It Will Happen and What It Will Mean. Oxford University Press.

Grieves, M., (2014). Digital twin: manufacturing excellence through virtual factory replication. White paper, 1, pp.1-7. https://www.researchgate.net/publication/275211047_Digital_Twin_Manufacturing_Excellence_through_Virtual_Factory_Replication

Jason R. C. Nurse, Sadie Creese, and David De Roure. (2017). Security Risk Assessment in Internet of Things Systems. IEEE IT Professional 19, 5 (2017), 20–26. https://doi.org/10.1109/MITP.2017.3680959

Kabisch, E. (2008). Datascape: A Synthesis of Digital and Embodied Worlds. Space and Culture, 11(3), 222–238. https://doi.org/10.1177/1206331208319147

Kallinikos, J., Aaltonen, A., & Marton, A. (2010). A theory of digital objects. First Monday. https://doi.org/10.5210/fm.v15i6.3033

Kuhn, T., Antonino, P.O. and Bachorek, A., (2020), September. A Simulator Coupling Architecture for the Creation of Digital Twins. In European Conference on Software Architecture (pp. 326-339). Springer, Cham. https://doi.org/10.1007/978-3-030-59155-7_25

Kutscher, V., Olbort, J., Steinhauer, C. and Anderl, R., (2020), July. Model-Based Interconnection of Digital and Physical Twins Using OPC UA. In International Conference on Applied Human Factors and Ergonomics (pp. 178-185). Springer, Cham. https://doi.org/10.1007/978-3-030-51981-0_23

Leonardi, P.M., 2012. Car crashes without cars: Lessons about simulation technology and organizational change from automotive design. MIT Press. https://mitpress.mit.edu/books/car-crashes-without-cars

Lu, Q., Parlikad Ajith, K., Woodall, P., Don Ranasinghe, G., Zhenglin, L., Heaton, J., Schooling, J., & Xie, X. (2020). Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus. Journal of Management in Engineering, 36(3), 05020004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000763

Macchi, M., Roda, I., Negri, E. and Fumagalli, L., (2018). Exploring the role of digital twin for asset lifecycle management. IFAC-PapersOnLine, 51(11), pp.790-79. https://doi.org/10.1016/j.ifacol.2018.08.415

Madaan, A., Nurse, J., de Roure, D., O'Hara, K., Hall, W., & Creese, S. (2018). A Storm in an IoT Cup: The Emergence of Cyber-Physical Social Machines (SSRN Scholarly Paper ID 3250383). Social Science Research Network. https://doi.org/10.2139/ssrn.3250383

Østerlie, T., & Monteiro, E. (2020). Digital sand: The becoming of digital representations. Information and Organization, 30(1), 100275. https://doi.org/10.1016/j.infoandorg.2019.100275

Rasheed, A., San, O. and Kvamsdal, T., (2020). Digital twin: Values, challenges and enablers from a modeling perspective. IEEE Access, 8, pp.21980-22012. http://creativecommons.org/licenses/by/4.0/

Reeves, K., & Maple, C. (2019). Realising the vision of digital twins: Challenges in trustworthiness. 39 (7 pp.)-39 (7 pp.). https://doi.org/10.1049/cp.2019.0164

Succar, B., (2019). BIMFramework, viewed 30 June, 2021, https://www.bimframework.info

Succar, B., (2021). BIMDictionary, viewed 21 April, 2021, https://bimdictionary.com/en/coupling-level/1

Succar, B., & Poirier, E. (2020). Lifecycle information transformation and exchange for delivering and managing digital and physical assets. Automation in Construction, 112, 103090. https://doi.org/10.1016/j.autcon.2020.103090

Succar, B., Saleeb, N. and Sher, W., (2016). Model uses: foundations for a modular requirements clarification language. Australasian Universities Building Education (AUBEA2016), pp.1-12. https://www.researchgate.net/publication/303013287_Model_Uses_Foundations_for_a_Modular_Requirements_Clarification_Language

Talkhestani, B.A., Jung, T., Lindemann, B., Sahlab, N., Jazdi, N., Schloegl, W. and Weyrich, M., (2019). An architecture of an intelligent digital twin in a cyber-physical production system. at-Automatisierungstechnik, 67(9), pp.762-782. https://doi.org/10.1515/auto-2019-0039

Van der Valk, H., Haße, H., Möller, F., Arbter, M., Henning, J.L. and Otto, B., (2020). A Taxonomy of Digital Twins. In Proc. 26th Americas Conference on Information Systems (pp. 1-10). https://www.researchgate.net/publication/341235159

Wang, T., Liang, Y., Yang, Y., Xu, G., Peng, H., Liu, A. and Jia, W., (2020). An intelligent edge-computing-based method to counter coupling problems in cyber-physical systems. IEEE Network, 34(3), pp.16-22. http://csc.sjtu.edu.cn/doc/2020-4.pdf

Yaqoob, I., Salah, K., Uddin, M., Jayaraman, R., Omar, M. and Imran, M., 2020. Blockchain for digital twins: Recent advances and future research challenges. IEEE Network, 34(5), pp.290-298. http://dx.doi.org/10.1109/MNET.001.1900661

Yoo, Y., Henfridsson, O. and Lyytinen, K., 2010. Research commentary—the new organizing logic of digital innovation: an agenda for information systems research. Information systems research, 21(4), pp.724-735. https://doi.org/10.1287/isre.1100.0322