# An investigation of the coupling of the physical and digital assets and resources across lifecycle stages in the built environment

by

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**Une enquête sur le couplage des biens et ressources physiques et numériques à travers les étapes du cycle de vie dans l'environnement bâti**

Saman DAVARI

**RESUME**

La numérisation rapide de l'industrie des actifs bâtis pousse à un couplage plus étroit des informations entre les actifs et les ressources physiques et numériques. Un tel couplage d'informations promet plusieurs opportunités aux parties prenantes de l'industrie en matière gains considérables en termes de performances et de valeur générées par la gestion intégrée de l'information. Dans le contexte des systèmes cyber-physiques (CPS) et des jumeaux numériques (DT), un nombre croissant d'études mettent l'accent sur les aspects techniques des CPS et des DT. Cependant, il manque encore des définitions, des dimensions, des caractéristiques et des concepts communs relatifs au couplage des informations du cycle de vie. Tirer pleinement parti de ces concepts nécessite de nouveaux concepts, principes et mécanismes pour définir et mettre en relation les divers composants qui comprennent le couplage des informations sur le cycle de vie des actifs et ressources physiques et numériques.

Cette thèse vise à aborder les lacunes et les problèmes en lien avec cette absence de conceptualisation du couplage au moyen d'une taxonomie définissant les couples d'informations sur le cycle de vie des actifs bâtis en fournissant les dimensions et les caractéristiques encadrant le couplage physique-numérique des actifs et des ressources dans l'industrie des actifs bâtis. De plus, un cadre conceptuel permettant la mise en œuvre des couplages physico-numériques est proposé pour opérationnaliser et instancier les dimensions clés de la taxonomie développée sur des cas réels. La taxonomie proposée et son cadre d'instanciation contribuent à l'effort visant à structurer le domaine de connaissances de la gestion de l'information du cycle de vie par le couplage des mondes physique et numérique dans l'environnement bâti.

**Mots-clés:** Couplage d'actifs, Taxonomie, Numérisation, Gestion du cycle de vie, Environnement bâti

**An investigation of the coupling of physical and digital assets and resources across lifecycle stages in the built environment**

Saman DAVARI

## ABSTRACT

The rapid digitalization of the built asset industry is pushing towards a tighter information coupling of physical and digital assets and resources. Such information coupling allows stakeholders to unlock opportunities for considerable gains in terms of performance and value generated through integrated information management. Within the context of Cyber-Physical Systems (CPS) and Digital Twins (DT)s, a growing number of studies are emphasizing on the technical aspects of CPS and DT. However, there still lacks a common definitions, dimensions, characteristics, and concepts pertaining to lifecycle information coupling. Taking full advantage of these concepts requires new constructs, principles, and mechanisms to define and put into relationship various components that comprise the lifecycle information coupling of physical and digital assets and resources.

This thesis aims to address existing coupling gaps and issues through a taxonomy of Built Asset Lifecycle Information Couples which provides the dimensions and characteristics framing the physical-digital coupling of assets and resources in the built asset industry. Additionally, a Coupling Action Instantiation Framework was proposed to operationalize and instantiate the key dimensions of the developed taxonomy in the real-world practices. The proposed taxonomy and its instantiation framework contribute 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, Lifecycle information management, Built environment

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| | |
|---|---|
| AC | Actual Cost |
| AEC | Architecture, Engineering, and Construction |
| AI | Artificial Intelligence |
| AML | Automation Markup Language |
| ANN | Artificial neural Network |
| AR | Augmented Reality |
| BIM | Building Information Modelling |
| BIME | BIM Excellence |
| CAD | Computer-aided Design |
| CDE | Common Data Environment |
| CLEVEL | Coupling Level |
| CE | Circular Economy |
| CPS | Cyber-Physical Systems |
| CPSM | Cyber-Physical systems machines |
| CPT | Capability Periodic Table |
| DM | Digital Model |
| DOA | Degree of Automation |
| DOT | Degree of Transparency |
| DR | Digital Record |
| DS | Digital Shadow |
| DSR | Design Science Research |

| | |
|---|---|
| DT | Digital Twin |
| DTH | Digital Thread |
| EOL | End-of-Life |
| FMU | Functional Mock-up Units |
| FTS | Food Traceability Systems |
| GIS | Geographic Information System |
| IFC | Industry Foundation Classes |
| IOT | Internet of Things |
| IS | Information Systems |
| ISO | International Organization for Standardization |
| LCA | Lifecycle Cost Assessment |
| LCC | Life Cycle Costing |
| LITE | Lifecycle Information Transformation and Exchange |
| LOA | Level of Accuracy |
| LOD | Level of Development/Detail |
| MEP | Mechanical, Electrical, and Plumbing |
| ML | Machine Learning |
| O&M | Operation and Maintenance |
| OIL | Ontology Interface Layer |
| OWL | Web Ontology Language |
| PACS | Picture Archiving and Communication System |
| PC | Personal Computer |
| PLM | Product Lifecycle Management |

| | |
|---|---|
| RF | Representational Fidelity |
| SNN | Simulated Neural Network |
| SQM | Sustainable Quality Management |
| TQM | Total Quality Management |
| TRU | Traceability Resource Unit |
| TUI | Tangible User Interface |
| UI | User Interface |
| USIBD | United States Institute of Building Documentation |
| VEP | Virtual Environment Platform |
| VLAN | Virtual Local Area Network |
| VPN | Virtual Private Network |
| VR | Virtual Reality |
| WLAN | Wireless Local Area Network |

# INTRODUCTION

The past decade has seen the rapid digitalization of the built asset industry which provides opportunities for considerable gains in terms of performance, quality, and value generation through the advanced digital information technologies and integrated systems. A strong majority of the latest developments in digitalization of the built environment are manifested through the coupling of physical and digital assets and resources (Yaqoob et al., 2020; Macchi et al., 2018). A growing number of studies are investigating the application of Digital Twins (DT)s in which a digital model reflects the life of its corresponding physical twin. Indeed, DTs has shown various benefits in changing the dynamics of construction process, manufacturing, smart cities, healthcare, and etc. (Mandolla et al., 2019).

However, the body of knowledge pertaining to DT has been mainly limited to its technical features and applications particularly in the context of built asset industry. According to Josifovska et al. (2019), inconsistent use of dimensions, terms, and definitions has made DT more difficult to comprehend across lifecycle stages. In fact, there still lacks a common basis to clarify what terms, definitions, concepts, dimensions, and enablers are needed to support lifecycle information coupling of the physical assets and their digital counterparts.

Another important issue is that key mechanisms to operationalize lifecycle information coupling of built assets and resources are still missing and need to be further developed. Such issues could be commonly evident at the organizational and management levels, where stakeholders would be unable to take full advantages of lifecycle information coupling and make effective decisions throughout the asset's lifecycle (Juarez et al., 2021). This results in huge information gaps between assets, people/machines, and resources (Lawrenz et al., 2021).

Although the concept of asset and information coupling has been explored in the context of Cyber-Physical Systems (CPS) (A. A. Akanmu et al., 2021), principles and characteristics of asset and information coupling has received less attention in the built asset domain. As a nascent field of study, new constructs – taxonomies, frameworks, mechanisms – are required to be developed for defining the core principles and characteristics of lifecycle information coupling in the built asset industry. While the concepts and terminology used to describe, study, and develop the domain are still evolving, several of these concepts must be coined to act as foundation to support the development and instantiation of theories, models, and frameworks applicable within this domain.

The abovementioned problems form the following main research question:
How can the concept of lifecycle information coupling of built assets and resources be characterized and framed to facilitate its adoption and implementation?

To identify potential solutions for addressing this research question, a review of current literature was performed. An increasing number of studies have proposed frameworks, models, and theories covering lifecycle information management of assets and resources. While the majority of these studies have formulized asset information management in a fragmented and rigid way, Succar & Poirier (2020) proposed "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" – to address existing barriers in digitalization of asset information management. The work set out in this thesis investigates and expands on key constructs of the LITE framework and focalises on the notion of built asset lifecycle information coupling.

In addition, many overlaps exist between the notion of built asset lifecycle information coupling and existing studies or practices in the fields of digital representation, digital twining, digital threading, and traceability systems. A comprehensive review of such concepts and their relationships to the concept of asset coupling can help to identify current trends, key challenges, and future potentials in the domain.

**Research goals**

The aim of this research is to develop an artefact aimed at structuring the body of knowledge and instantiating various aspects of asset coupling in the context of built asset industry. To achieve this goal, this research proposes a taxonomy of lifecycle information coupling of built assets and resources, as well as an instantiation framework for identifying required coupling actions, mechanisms, and principles.

Therefore, the following research objectives are summarized:

- To define the constructs, principles, and mechanisms needed to support the concept of lifecycle information coupling of built assets and resources in the built asset industry.
- To articulate these defined constructs, principles, and mechanisms within the taxonomy of lifecycle information coupling of built assets and resources.
- To operationalize these defined constructs, principles, and mechanisms and enable their application in the built asset industry through a taxonomy and its instantiation framework.

**Structure of the thesis**

This thesis is organized into five chapters. The introduction described the context of research and highlights critical problems in the state-of-the-art. The research question and objectives are also established. In chapter one, a background on the studies and practices regarding to the concept of DT, digital representation theories, asset coupling, the LITE framework, Digital Threads (DTH)s, and information traceability systems is provided.

The adopted methodology of the research is introduced in chapter two. This chapter also presents the selected case studies for evaluation purposes. The third chapter introduces the main solutions and constructs of the research. The result of the research and key findings are specified in chapter four. All the key findings of the research are further discussed and contextualized in chapter five. This chapter ends with research limitations and future work.

Finally, a summary of proposed solutions, key findings, and main contributions of the research is provided in the conclusion section.

# CHAPTER 1

# LITERATURE REVIEW

In this chapter, a literature review was performed to review the current state of the research, key challenges, and future potentials on the related subjects. The review will provide a background on the concept of Digital Twin (DT), representation theories in the context of lifecycle information coupling, asset and information coupling across domains, LITE framework, and information traceability of built assets and resources. This review helped to develop a taxonomy for built asset lifecycle information coupling as well as an integrated framework for ensuring the methods and activities through which Lifecyle Information Couples are created and maintained.

## 1.1 A Shift to the Digital Twin (DT)s Paradigm

Within the context of CPS, recent studies have extensively investigated the application of Digital Twins (DT)s, in which a digital model reflects the state of a physical asset at any given moment (Macchi et al., 2018). The application of DTs has shown promising results in allowing industry practitioners to visualize and monitor performance data at different levels of details and granularity across the lifecycle phases of assets (Camposano et al., 2021). As the benefits of DTs are becoming more evident, the number of scientific publications focused on the digital twinning of the built environment has been surging. However, with all this attention, the concept of DT has become vague and inaccurate due to the way the term "digital twin" has been used since its coining.

This section provides an overview on the definition of DT, the main problems that this approach is trying to address, and its key components and dimensions using existing taxonomies found in the literature.

### 1.1.1 Definition of Digital Twin

While the idea of digital twinning is getting more attentions in the built asset industry, various definitions have been proposed by scholars and practitioners across domains. Based on the existing definitions, it is still difficult to quickly gain a profound and clear understanding of the degree to which the different definitions overlap. Table 1.2 represents the most common definitions of DTs that have been widely used in the literature of various disciplines.

Table 1.1 Most common definitions of DTs (based on number of citations)

| Ref | Definition | Citation (As of December 2022) | Context | Year |
|---|---|---|---|---|
| (Grieves & Vickers, 2017) | "The Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. Digital Twins are of two types: Digital Twin Prototype (DTP) and Digital Twin Instance (DTI). DTs are operated on in a Digital Twin Environment (DTE)." | 1492 | Manufacturing | 2017 |
| (Glaessgen & Stargel, 2012) | "Digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin. | 1506 | Aerospace | 2012 |

| Ref | Definition | Citation (As of December 2022) | Context | Year |
|---|---|---|---|---|
| | Meanwhile, digital twin consists of three parts: physical product, virtual product, and connected data that tie the physical and virtual product.” | | | |
| (Yitmen & Alizadeh salehi, 2021) | “A digital twin refers to a virtual replica of a physical building or infrastructure that integrates real-time data, simulations, and digital models to provide a comprehensive understanding of the asset's design, construction, operation, and maintenance.” | 104 | AEC | 2021 |
| (Tao et al., 2019) | “[A] Digital Twin consists of three parts: physical product, virtual product, and connected data that tie the physical and virtual product. [...] the following characteristics of Digital Twin are summarized: (1) Real-time reflection. [...] the virtual space [...] can keep ultra-high synchronization and fidelity with the physical space. [...]” | 1161 | Mechanical Engineering | 2019 |

### 1.1.2 The Need for Digital Twin in the Built Asset Industry

In recent decades, the widespread application of Computer-aided Design (CAD) tools and Building Information Modelling (BIM) has provided several new insights and capabilities for lifecycle information management of the built asset (Deng et al., 2021). Despite these advances in underlying geometric and semantic information of building elements, BIM can only manage static data of the built assets (S. Tang et al., 2019), and integration of real-time sensing data with digital models has been challenging across an asset's lifecycle. Although several studies have proposed Internet of Things (IoT) techniques to facilitate real-time data integration between physical and digital assets, other issues such as real-time visualization, prediction and automated feedback control for changing of asset parameters have remained unsolved (Deng et al., 2021). In addition, current offline simulation methodologies lack accuracy and fidelity with respect to the actual state of a physical asset. In theory, a simulation consists of dynamic processes and activities which are developed overtime (Van der Valk et al., 2020). This can be carried out by experimental models which cover all dynamic aspects of an asset’s life cycle under different operational scenarios (Schluse & Rossmann, 2016).

Another important aspect in lifecycle information management of the built assets is the idea of comparison. The built asset industry is associated with continuous changes from planning to operation and maintenance (O&M) stages (Bolshakov et al., 2020). Although BIM technologies and processes provide opportunities to compile and generate virtual asset information of physical assets, they are still inefficient, as stakeholders may need to look at the physical asset and manually compare the relevant virtual information with their physical counterpart to identify their differences and similarities (Grieves, 2015).

The implementation of DT unlocks numerous opportunities to address mentioned issues. Real-time data sensing and visualization are common DT requirements (Bado et al., 2022). Applying advance visualization tools on DTs data can disclose hidden problems and faults in advance (Yaqoob et al., 2020). Unlike classic simulation methodologies, DT uses a wide range of virtual models to represent past, current, and future conditions of physical assets using input data and outputs (Boje et al., 2020). Predicting future behaviour of physical assets is an important feature of DT, particularly at the organizational level, thereby long-term decision-making requires reliable and accurate data (Kuster et al., 2017). Regarding comparison of physical and digital built assets, a DT model includes multiple quantitative and qualitative characteristics, as well as tolerance corridors which enable users to identify positive and negative deviations of processed data (Grieves, 2015).

In general, the ideal DT is expected to proactively support real-time data transformation and exchange, reliable simulation of the actual built assets, automatic control feedback and effective decision making across entire asset's lifecycle.

### 1.1.3 Key Components and Dimensions of Digital Twin

To conceptualize the coordination between physical and digital assets, a considerable number of DT models have been introduced by academia and industry. The first model was conceptualized by Michael Grieves in 2003 focusing on how physical manufactured products meet their as-planned specifications using DT capabilities in data visualization and exchange (Grieves & Vickers, 2017). The model (Figure 1.1) contains three principal components: (1) physical space; (2) virtual space; and (3) data connection space.

The physical space includes elements (e.g. sensors and devices) that are responsible to physically capture data and transmit them to the virtual space (Zheng et al., 2019). The virtual space is composed by virtual environment platform (VEP) and multiple DT models to enable various virtual operations such as control, prediction, or visualization (Juarez et al., 2021). The data connection space links the raw or proceeded data from physical space to the virtual space (Borangiu et al., 2020) through the connection loops (Boje et al., 2020).

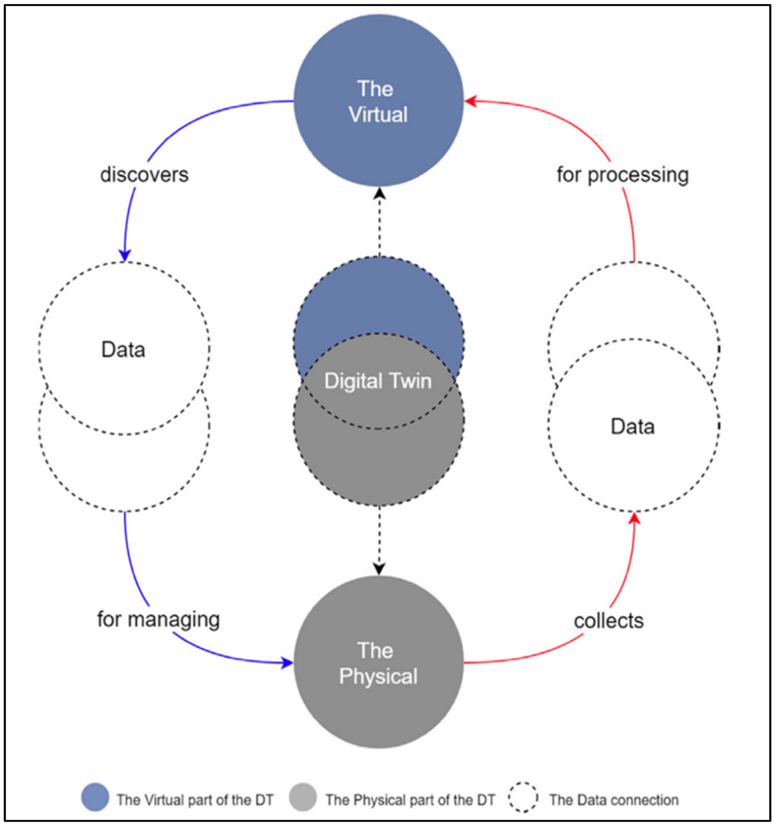


Figure 1.1 The main components of a DT
Taken from Boje et al. (2020)

Well after Michael Grieves proposed this conceptual model, scholars and practitioners from various domains started to pay attention to potential of DTs to connect physical and virtual worlds (El Saddik, 2018). Since then, a growing number of studies are focusing on the practical application of DTs in real-world experiments (Uhlenkamp et al., 2019). However, the main principles, dimensions, and metrics behind the term still need to be further investigated and explained (Haße et al., 2020).

Generally, a shift from traditional information management models to DTs is meaningful if new possibilities emerge from the coupling of physical and digital built assets. This includes tighter coupling between built assets to accurately represent the actual state of physical referents, the introduction of more mature mechanisms for data acquisition and exchange over an asset lifecycle, the emergence of enabling technologies, and the definition of all potential coupling metrics and characteristics in the built asset industry.

### 1.1.4 Current Taxonomies and Ontologies of Digital Twins

The models discussed above have mainly focused on conceptualization of DTs and its system architectures and applications. However, the principles and terminology used to describe, study, and develop the domain are still evolving (Juarez et al., 2021). In response to ongoing trends towards identification of central characteristics and features of DTs in the built asset industry, Haße et al. (2020) attempted a taxonomy (Figure 1.2) to unify all definitions and elements of DTs from the existing literature. The proposed taxonomy in this study includes eight dimensions, corresponding to characteristics that can be applied and extended to provide an understanding of DTs. The mutual exclusivity of dimensions describes characteristics that cannot happen simultaneously.

| Dimension | Characteristics | | | Exclusivity |
|---|---|---|---|---|
| Data Link | One-Directional (55) | Bi-directional (144) | | Mutual |
| Purpose | Processing (212) | Transfer (37) | Repository (30) | Not |
| Conceptual Elements | Physically Independent (75) | Physically Bound (99) | | Mutual |
| Accuracy | Identical (123) | Partial (50) | | Mutual |
| Interface | M2M (89) | HMI (140) | | Not |
| Synchronization | With (179) | Without (20) | | Mutual |
| Data Input | Raw Data (144) | Processed Data (106) | | Not |
| Time of Creation | Physical part first (132) | Digital part first (17) | Simultaneously (34) | Mutual |

● Definition of Glaessgen and Stargel 2012
● Definition of Grieves 2014 & Grieves and Vickers 2017
● Definition of Tao et al. 2018
■ Most used Characteristic

Figure 1.2 The taxonomy of DT
Taken from Haße et al. (2020)

Similar study has conducted by Yaqoob et al. (2020) and Juarez et al. (2021), focusing on DTs levels, applications, terminologies, DTs categories, enabling technologies, key objectives.

Milligan (2022) proposed a DT capability periodic table (CPT) classifying key capabilities of the DT that are required to address various case studies in the construction industry (Figure 1.3). These capabilities include: (i) Data Services; (ii) Integration; (iii) Intelligence; (iv) UX; (v) Management; and (vi) Trustworthiness. Such capabilities were set at different levels to cover most of the functional and representational requirements of use cases. Each capability was decomposed of sub-capabilities to provide more granular characteristics of DT such as data transformation, reporting, system monitoring, security, visualization, and etc. In addition, the author provided stakeholders a workflow to identify steps needed for implementation of classified capabilities in the construction industry.

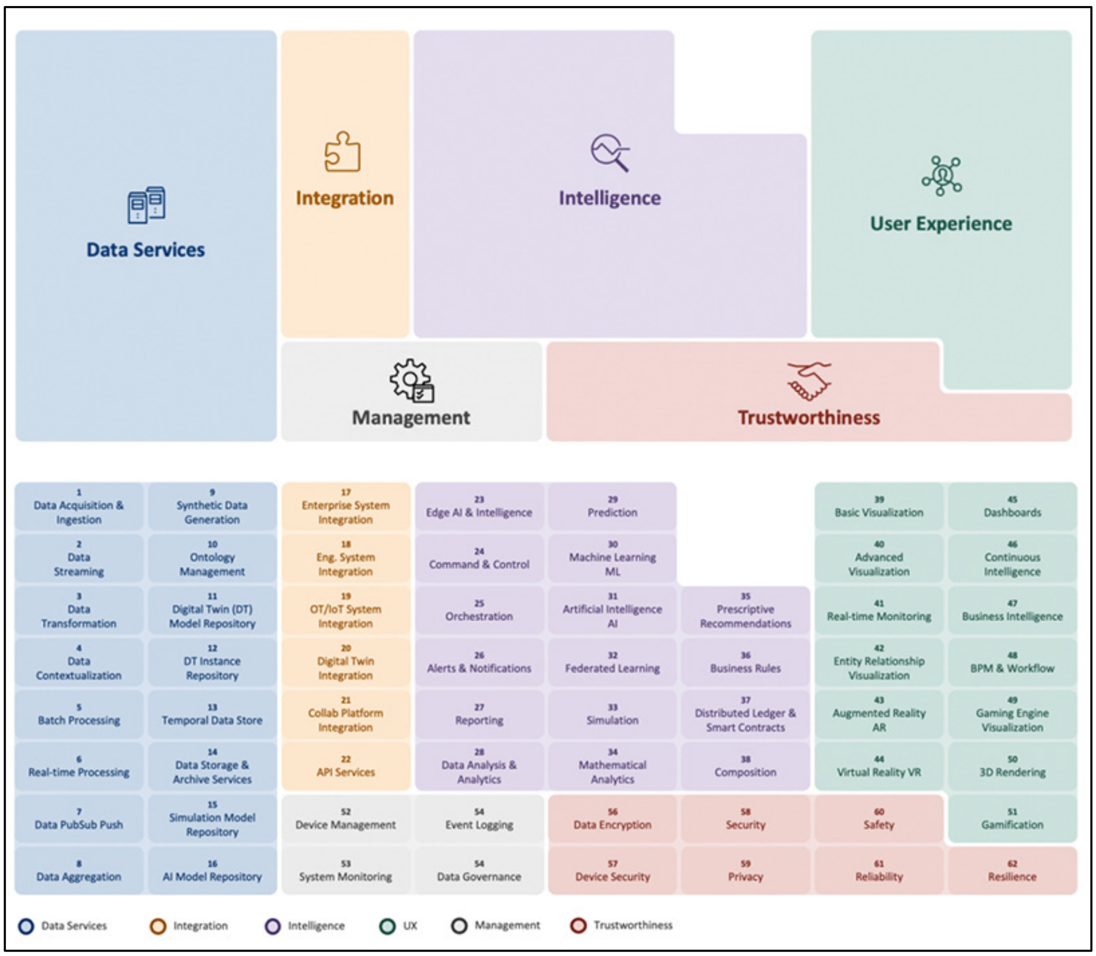


Figure 1.3 The digital twin CPT
Taken From Milligan (2022)

In addition to taxonomies, ontologies can be used to take a full advantage of the capacities of DT and identify specific and clear nature of a digital twinning process. In the manufacturing domain, Negri et al. (2016) conducted a literature review on the existing ontologies and selected the most appropriate ontologies for a digital twinning process including OIL (Ontology Interface Language), OWL (Web Ontology Language), AML (Automation Markup Language), FMU (Functional mock-up units), and OWL Lite. For example, FMU can be used to simulate different behaviours of a DT (e.g. energy consumption, availability of digital models), and AML has been widely used to develop the semantic data model of a physical asset (e.g. plans, paths, safety variables). While the list of potential ontologies is rapidly growing, each ontology has different characteristics that can be implemented according to a specific use case for better describing of a physical asset and its variations.

## 1.2 Digital Representation of Physical and Digital Built Assets

Digital representation is associated with creation of different forms of physical phenomena (Bailey et al., 2012). Digital representations occur when data is collected and algorithmically manipulated from physical referents (Østerlie & Monteiro, 2020). Consecutive manipulation of data results in "computational rendition of reality" in which representation is algorithmically decoupled from its origin and physical referent (Orlikowski, 2000).

### 1.2.1 The Nature of Representation

The nature of representation can be categorized and distinguished based on different kind of signs such as indices, icons, and symbols (Peirce, 1974). Indices mirror the behaviour of their physical counterpart regardless of resemblance, often through cause-and-effect relationship. Icons represent a physical asset by resemblance. This resemblance can be depicted using abstract visualizations such as sketches, CAD, or photographs (Bailey et al., 2012). Symbols emphasize on norms and habits of physical assets through an arbitrary link. The majority of symbols are generated from what is accepted in society (Peirce, 1974). There are less resemblance and dependency between physical assets and their symbols. Digital representation uses symbols to simulate and predict the behaviour of a physical asset in an indirect manner (Østerlie & Monteiro, 2020).

### 1.2.2 Representation Theories

From a theoretical point of view, representation of physical and digital objects, processes, and qualities has been widely investigated by scholars based on different types of virtual works. While some proponents argue that representation theory should be tailored to specific applications and circumstances, others argue that the plurality and permeability of the physical and the digital can be broadly investigated, embracing different forms of reality and unreality. As an example of the first viewpoint, Burton-Jones & Grange (2013) theorized the unique nature of representation for "effective use" of Information Systems (IS) and identified "Representational fidelity" and "Transparent interaction" dimensions to connect the level of trust in digital artefacts with the accuracy in representation of real world domains. The "Representational fidelity" here implies the extent to which a representation is accurate, and the "Transparent interaction" refers to accessibility of users to deep structure of a system-provided representation.

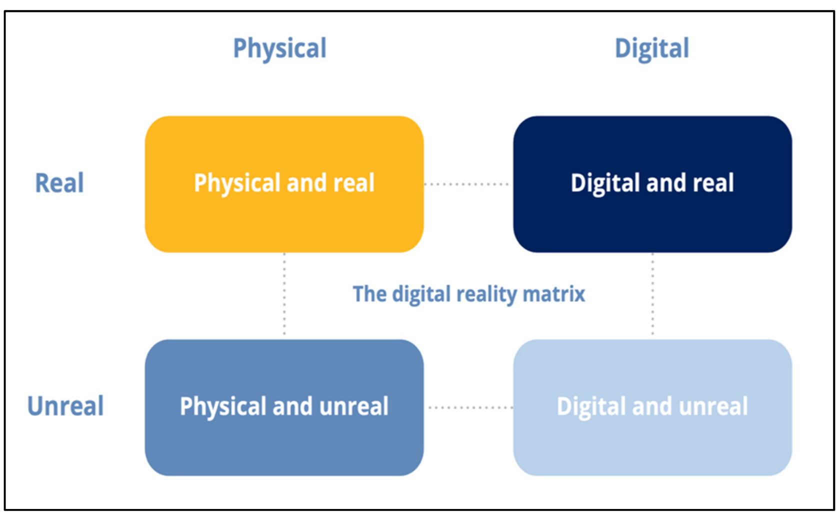


Figure 1.4 The digital reality matrix
Adopted from Boellstroff (2016)

Unlike mentioned contemporary representational theories, Boellstorff (2016) proposed the "digital reality matrix" (Figure 1.4) to understand the relationship between the digital and the physical with the real and the unreal. The author in this study emphasizes the urgent need to define precisely how digital can be made real as physical and how physical assets become unreal. According to Hine (2015), there is an opposition in the current distinction between the real world and virtual worlds. By opposing this false assumption that "virtual world" is always unreal and "physical world" is always real, Table 1.2 represents possible examples for each cell of the digital reality matrix. Such oppositions regarding the reality or unreality of physical and digital assets provide insight into the potential redefinition of the boundaries between – what is perceived as – reality and unreality in the context of built asset industry.

Table 1.2 Physical-digital and real-unreal conflations in nature

| Conflation | Description and examples |
|---|---|
| Physical and real | A tangible object, thing, or phenomenon that is physical in nature such as a rock, door handle, or a table. |
| Physical and unreal | A tangible object, thing, or phenomenon that is based on imagination and fantasy such as a play or theatrical performance. |
| Digital and real | An intangible object, thing, or phenomenon that is virtual in nature but can be perceived as real such as a plot of land in the metaverse or learning French online and being able to speak French. |
| Digital and unreal | An intangible object, thing, or phenomenon that is virtual in nature such as an avatar in a digital model of a building or weather changes in a computer game. |

## 1.3 Asset and Information Coupling Across Domains

The concept of asset and information coupling provides enhanced decision support and insight across the asset's lifecycle stages. The existing definitions, mechanisms, and characteristics of asset and information coupling will be explained in this section.

### 1.3.1 Definitions of Asset and Information Coupling

According to Succar (2019), asset coupling means "the development and/or maintenance of digital assets so they accurately match the physical Assets they represent. Asset Coupling translates changes in one asset (e.g. a change in the state or location of a component in real space) to changes in the coupled asset (in virtual space)". The term "Asset" here refers to a physical (e.g. a component or part) or digital (e.g. 3D model) entity that has value to an organization (Succar & Poirier, 2020). The scales of asset coupling across built asset industry include facility, system, component, and part (Succar, 2009).

In the simulation process, the states of asset coupling can be either "tight coupling" or "decoupling" (Lu, Parlikad, et al., 2020). "Tight coupling" is a state in which digital representations are highly dependent on physical referents (Bailey et al., 2012). In contrast, "decoupling" occurs when there is further independency or correspondence between digital and its physical counterpart (Østerlie & Monteiro, 2020). Zhang et al. (2021) proposed "Decoupling ability", emphasizing on the ability of a complex digital model to be decoupled from its physical referent and transformed into multiple smaller digital models.

### 1.3.2 Key Characteristics of Asset and Information Coupling

The most important aspect of asset coupling is information flow and exchange which enable decision making in real-time by a number of different types of actors (Boje et al., 2020). The type of data link specifies how information flow takes place between physical and digital assets (Autiosalo et al., 2020), which can be either bi-directional or Uni-directional (Haße et al., 2020). Approaches to asset and information coupling goes beyond manual data acquisition (Jagusch et al., 2021), since management of bi-directional data links and exchange requires active and automated data acquisition (Haße et al., 2020).

The extent of data linking can be measured by "Coupling Level (CLevel)" (Succar, 2019), which outlines the level of connectedness between physical and digital assets. The CLevel

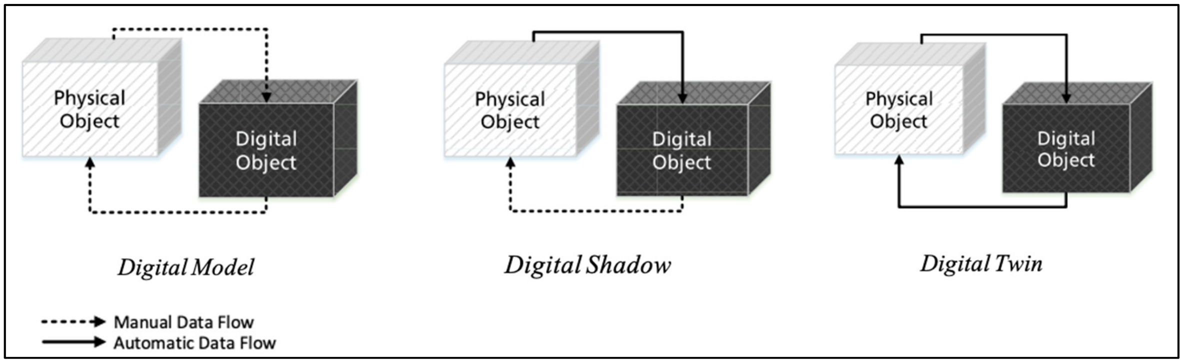


Figure 1.5 Levels of data integration between physical and digital assets
Taken from Kritzinger et al. (2018)

includes four levels: (0) No Coupling; (1) Low Coupling; (2) Medium Coupling; (3) Medium-High Coupling; and (4) High Coupling – Mirroring. A high CLevel indicates that changes are mirrored in real time, whereas a low level indicates a delayed or partial change. Similarly, Kritzinger et al, (2018), identified the "Level of Data Integration" as a dimension to evaluate the extent of integration between physical and digital assets (Figure 1.5). Such integration has classified in three kinds: (1) Digital Model (DM); (2) Digital Shadow (DS); and (3) Digital Twin (DT). A "Digital Model" refers to representation of a physical referent through manual one-directional data flow. Instead, if there is an automatic one-directional data flow between the physical object and digital model, it will be called "Digital Shadow". A "Digital Twin" in this study has characterised as a real instance of a physical object, which reflect the behavior of its physical counterpart through automatic bi-directional data flow (Juarez et al., 2021).

Another requirement for asset and information coupling is being able to predict and optimise the state of physical and digital assets across their lifecycle stages (Boje et al., 2020). Some studies have proposed the creation of a "predictive couple", which is a physics-based couple that receives real-time data and exploit it as a pattern to predict the behaviour of assets throughout of their lifecycle phases (Rasheed et al., 2020).

### 1.3.3 Current Mechanisms of Asset and Information Coupling

To increase the degree of coupling between physical assets and digital representations, effective mechanisms have been proposed by scholars and practitioners from various knowledge and industrial domains (Reeves & Maple, 2019). For instance, Østerlie & Monteiro (2020) identified three mechanisms for making a digital representation organizationally real: (1) signal aggregation in which irrelevant sensor data are weeded out and sorted to obtain the most reliable arrangement for analysis purposes (Yaqoob et al., 2020); (2) signal coupling in which digital and physical representations of a phenomena are coupled; and (3) signal calibrating in which digital representations are correlated with other representations in order to materialize data into knowledge for day-to-day organizational uses.

Among different types of virtual works, simulation offers a great potential to increase the tight coupling between virtuality and reality (Bailey et al., 2012). Simulation provides "what if" scenarios (De Roure et al., 2019) and predict the behavior of physical assets with high fidelity (Boje et al., 2020). In the coupling process of physical and digital assets, simulation should be executed in parallel with the changes in real world (Ashtari Talkhestani et al., 2019). While advanced simulations make people independent from actual physical objects, further validations and tests on the simulated models are required to ensure the tight coupling between simulations and physical referents (Bailey et al., 2012).

From a socio-technical perspective, De Roure et al. (2019) categorized different types of coupling mechanisms, focusing on the intersection between digital world and social behavior. Physical coupling, social coupling, lifecycle coupling, indirect data coupling, and other coupling examples have been described to facilitate complex couplings on the IoT ecosystem. Similarly, the coupling between humans and social machines was further investigated by Madaan et al. (2018) through the lens of IoT devices. The authors of this study adopted a cyber-physical social machines (CPSMs) approach to observe potential tight couplings between IoT devices and CPSMs platforms. This approach demonstrated that tight coupling occurs when web-based social machines have high correspondence with IoT physical devices such as sensors or actuators. Such IoT devices are wirelessly connected to the Internet, allowing for tight coupling between various web-based systems and physical infrastructures (Nurse et al., 2017).

### 1.3.4 Enabling Technologies of Asset and Information Coupling

To enable effective data link and acquisition, a considerable amount of work has been conducted across domains to identify potential digital information tools. For example, Omar & Nehdi (2016) categorized the data acquisition tools into four high-levels solutions: (1) enhanced IT; (2) geospatial technologies; (3) imaging technologies; and (4) automated reality. Depending on types of virtual work, each category in this study can facilitate digital representation of built asset in terms of real-time data processing, durability of devices, user interface (UI) and cost efficiency.

Other studies have emphasised on the applications of IoT and Artificial Intelligence (AI) to facilitate accuracy and reliability of data processing between digital representation and physical asset (El Saddik, 2018). For instance, Yaqoob et al. (2020) listed current enabling technologies in the construction domain (Table 1.3) and identified blockchain as a promising solution to improve data traceability, trustworthiness, data security, and immutability of asset and information coupling of built assets.

While digital technologies are rapidly evolving, Nnaji & Karakhan (2020) identified that many users still have difficulties to exploit the full potential of these technologies for asset and information coupling purposes. For example, current domain-based BIM models provide only a “partial” representation of a physical asset during coupling process, and integration of multiple BIM-based models require considerable amount of work to identify clashes or compliances (Seracino, 2010).

Table 1.3 Role of enabling technologies in asset and information coupling
Taken from Yaqoob et al. (2020)

| **Enabling technologies** | **Role in asset and information coupling** |
|---|---|
| Cloud computing | • Offers storage services for a large amount of high-frequency time-series data.<br>• Digital couple can leverage advanced analytics and cognitive capabilities by using cloud workstations. |
| 3D Simulation | • Help to better visualize and understand the product/process design.<br>• Allow adding motion and depth in product/process design that needs to be replicated. |
| IoT | • Miniaturization of IoT technologies enables the creation of digital couples.<br>• Enable sharing of data between virtual and physical objects using a system of sensors. |
| 5G networks | • Offer much faster connection speeds between virtual and their real objects |
| Big data-driven technologies | • Offer efficient storage, processing, and analysis services for digital data<br>• Applying analytic solutions help to get insights into large amounts of synced data |
| Blockchain | • Offers greater transparency<br>• Improves traceability and transactions speed |

## 1.4 The LITE Framework and Information Lifecycle Couples

The rapid digitalization of built asset lifecycle information and its integrated management require digital platforms connecting design, delivery, and utilisation of physical and digital built assets (Succar & Poirier, 2020). While legacy concepts and models are being standardized to harmonize better data transformation and exchange between different construction actors, they lack responsive and productive constructs aiming towards information coupling of physical and digital built assets.

In addition, traditional practices have formulized asset information management in a fragmented and rigid way in which lack of relationship between as-planned and as-built stages limits insight and decision-making of users across an asset's lifecycle (Alnaggar & Pitt, 2019). To overcome the existing barriers in digitalization of lifecycle information management, Succar & Poirier (2020) proposed "Lifecycle Information Transformation and Exchange (LITE)" framework as both an expandable and open access platform (Figure 1.6).

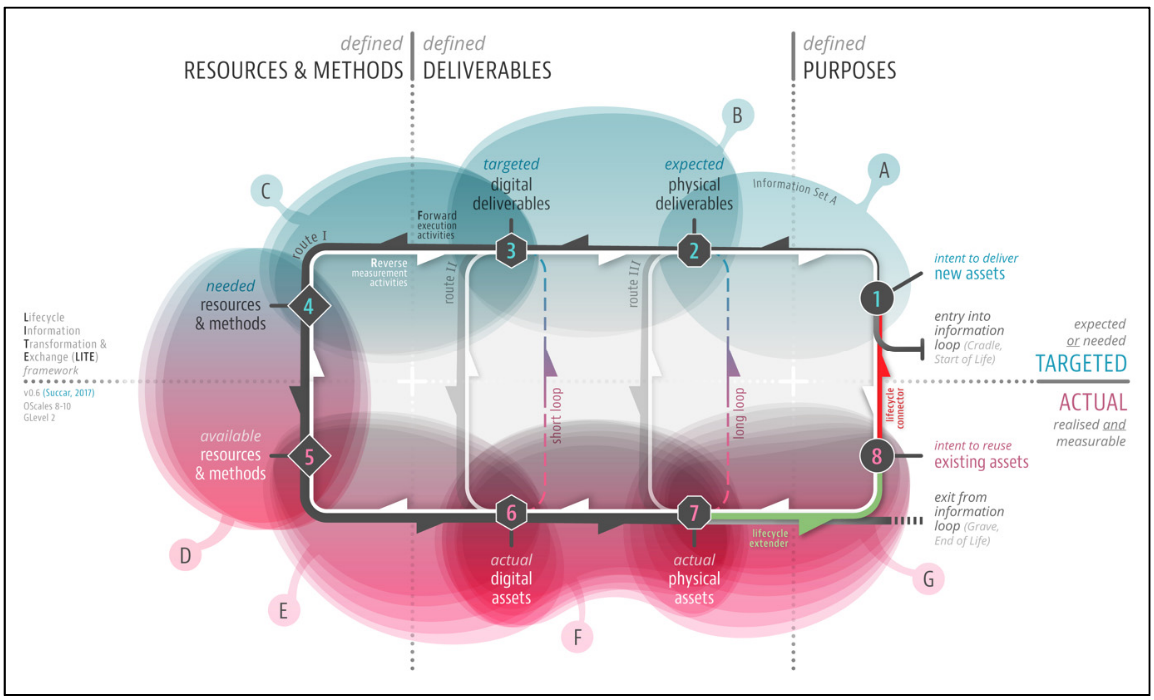


Figure 1.6 Overview of the LITE framework

Taken from Succar & Poirier (2020)

### 1.4.1 Key Characteristics of the LITE Framework

The LITE framework allows information to circulate and evolve through open and closed loops according to specific routes and across distinct milestones. Information flow takes place 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 benefiting for emergent applications of machine learning (ML) 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, assets 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.

### 1.4.2 Information Lifecycle Couples in the LITE Framework

The LITE framework contains 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. Figure 1.6 shows the Milestones Couples, reflecting the information statuses and states within the framework. The targeted and actual information statuses are linked by four vertical 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's lifecycle. The one deserving attention here is that Built Asset lifecycle information coupling should not be limited to DTs of physical assets. As highlighted in Figure 1.7, 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 coupling model that detail all built asset lifecycle information couples and their characteristics.

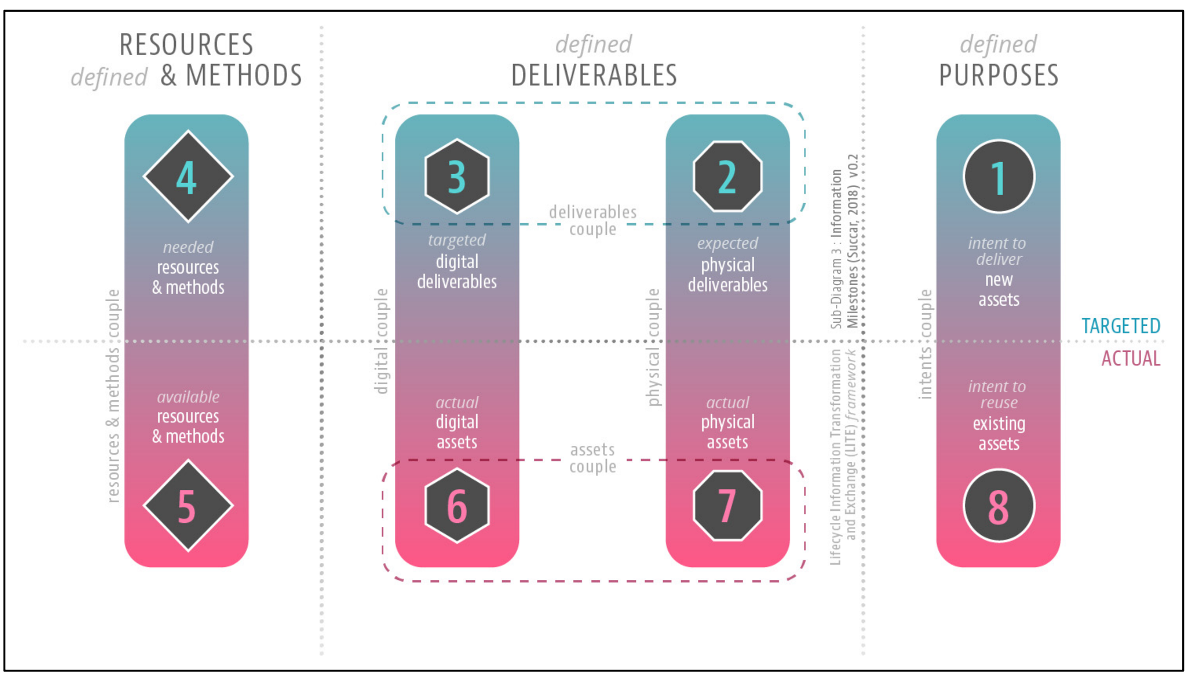


Figure 1.7 The LITE framework - Information Couples
Taken from Succar & Poirier (2020)

## 1.5 Traceability of Physical and Digital Built Assets and Resources

As mentioned earlier, effective asset and information coupling relies heavily on the information flow and exchange between physical and digital assets and resources. One of the main challenges hindering this full potential lies with absence of real-time "traceability" of communicated information among multiple stakeholders and resources (Z. Wang et al., 2020).

As part of an independent review of building regulations and fire safety commissioned by the UK Government, Hackitt (2018) emphasized on slow adoption of traceability techniques by construction industry in comparison with other sectors such as manufacturing or food industries.

While built asset industry is associated with dynamics and uncertainties in lifecycle information management (Zhuang et al., 2021), it is crucial to identify potential traces across an asset's lifecycle and translate them into knowledge for better decision-making and insight (Brandín & Abrishami, 2021). This section will review the notation of traceability and highlight key challenges and potentials in the context of asset and information coupling.

### 1.5.1 Definition of Information Traceability

Based on the reviewed literature, there is currently no formal and comprehensive definition for traceability in the built asset industry (Watson et al., 2019). Instead, different aspects of traceability have been identified and framed based on the purposes and methods of each project (Katenbayeva et al., 2016). While the notation of traceability is rapidly evolving, most of the definitions can be found in the food industry where traceability plays an important role to enclose information related to agricultural processes, consumer needs, business marketing, and etc. Table 1.4 represents the most common definitions of traceability across domains.

Table 1.4 Definitions of information traceability across domains

| Ref | Definition | Context | Year |
|---|---|---|---|
| (Olsen & Borit, 2018) | “The ability to access any or all information relating to that which is under consideration, throughout its entire lifecycle, | Food industry | 2018 |
| (Brandín & Abrishami, 2021) | “Traceability involves knowing where the product or raw material comes from, real-time location throughout the supply chain, and its conditions regarding pre-set quality at each stage of the roadmap”. | AEC | 2021 |
| (K.-S. Wang, 2014) | “The ability to trace the history, application, or location of an entity by means of recorded identifications”. | Manufacturing | 2014 |
| (Gotel & Finkelstein, 1994) | “The ability to describe and follow the life of a requirement, in both a forwards and backwards direction (i.e., from its origins, through its development and specification, to its subsequent deployment and use”. | Software Engineering | 1994 |

### 1.5.2 Barriers in Implementing Information Traceability

There are currently no formal standard or guideline that provides practical suggestions to implement traceability in the construction management (Katenbayeva et al., 2016). The current standards and policies such as BES 6001 (Upstill-Goddard et al., 2015) or ISO 9001 (Ingason, 2015) are mainly addressing traceability issues in relation to quality management and responsible sourcing of construction materials and products (Upstill-Goddard et al., 2011).

This leads to poor understanding of the concept of traceability and results in what can be termed as an "information gap" among multiple stakeholders and resources (Lawrenz et al., 2021).

It is extremely important to close the information gap to truly enable the implementation of traceability principles. Watson et al. (2019) identified varied nature of project procurement, complexity of information chain and very long project and asset lifecycles as the main barriers to close the information gap in the built asset industry.

In addition, lack of automated solutions would result in late signal processing, duplication and manipulation of data which need to be addressed for functional and non-functional traceability of built assets and resources (Brandín & Abrishami, 2021). Bosona & Gebresenbet (2013) conducted a systematic literature review and categorised current barriers in implementing traceability of food products from logistic and supply chain point of view (Table 1.5).

In addition, traceability of all links made to enclose valuable information of built assets would be complicated if there is no automated and integrated methods particularly in large projects (Pinheiro, 2004). Another major concern is consistent changes in requirements of a project which must be dynamically traced and recorded (Ramesh et al., 1995). To understand how a change in a requirement will affect other systems or sectors, further "information transparency" is required during the traceability process (Watson et al., 2019). Ensuring information transparency can be divided with a right mix of automated and manual methods (Pinheiro, 2004).

Table 1.5 Major driving forces in implementing traceability
Taken from Bosona & Gebresenbet (2013)

| **Category** | **Driving forces** |
|---|---|
| Regulatory concern | • Introduction of new safety legislations and efforts to maintain market power and stay in the business i.e. partners of food supply network have to have FTS to stay in business |

| Category | Driving forces |
|---|---|
| | • Ownership disputes |
| Safety and quality concern | • Limiting the potential causes and spread of diseases related to contamination by radioactive materials and/or bioterrorism and counterfeiting<br>• Tackling safety crises i.e., increasing incidence of product-related safety hazards<br>• Value preservation and value addition in the products |
| Social concern | • Addressing declining consumer confidence in product in the market and public concern about rising incidence of product-related illnesses and deaths<br>• The gradual shift from quantity-oriented to quality/safety-oriented supply chain due to changing lifestyles and rising income of consumers demanding ingredients.<br>• The increase in awareness of consumers about their health.<br>• The need to identify genetically modified organisms (GMO) and non-GMO agricultural chains (to address the concern of consumers).<br>• The increase in awareness of consumers about their health and weight control, e.g. quality and nutritional values of products.<br>• Better market access and affordability of assets and resources. |
| Technological concern | • Advancement in technology (encouraging traceability) |

### 1.5.3 Future Potentials of Information Traceability

#### 1.5.3.1 Traceability Framework

While the importance of information traceability is becoming evident, many academic publications stress on the integrated frameworks to address mentioned barriers in the built asset industry. Only a few numbers of traceability framework and guidelines can be found in the literature such as requirement traceability framework (Jansen-Vullers et al.,2003), theoretical traceability framework for sustainability (Katenbayeva et al., 2016), and traceability framework for digital recording of the built assets (Watson et al., 2019). The guidelines from such frameworks can be implemented to couple potential traces and attributes of communicated information across an asset's lifecycle. Many studies have agreed on four elements of traceability frameworks (Jansen-Vullers et al., 2003): (1) Physical-digital integrity; (2) data collection; (3) product identification and process linking; (4) reporting.

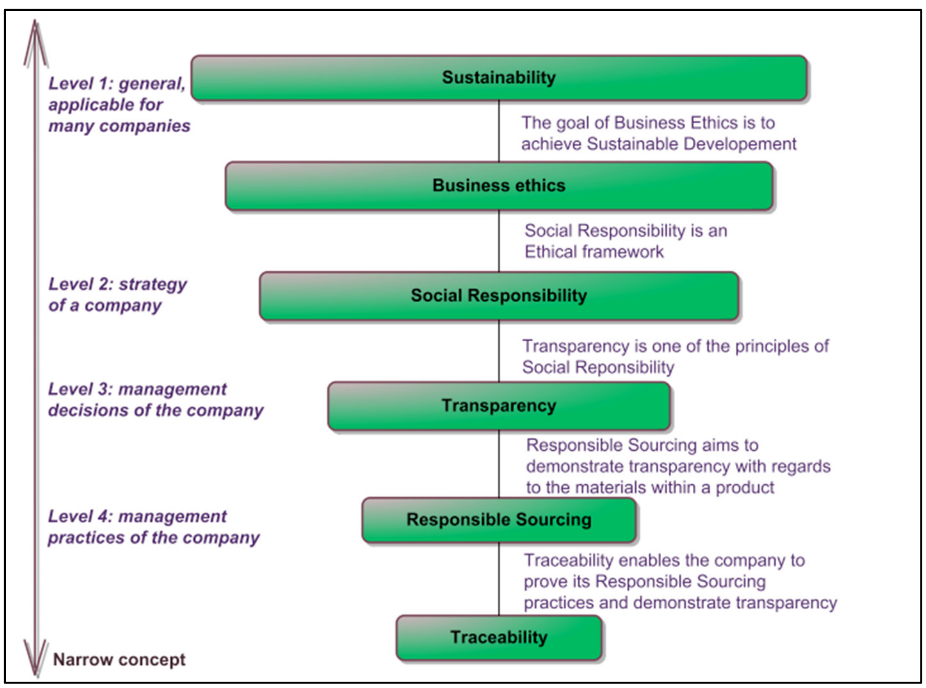


Figure 1.8 The concepts related to traceability
Taken from Katenbayeva et al. (2016)

Depending on traceability purposes and expected outcomes, these elements can be potentially framed through the concept of asset and information coupling. In addition, various drivers, concepts, and enablers have been proposed in the literature. Katenbayeva et al. (2016) analyzed potential traceability concepts through a granular diagram (Figure 1.8) and highlighted sustainability pillars - environmental, economic, and social - as the main areas that a traceability framework must be implemented.

#### 1.5.3.2 Digital Record (DR)

Other studies have emphasized on the role of "Digital Record (DR)" in traceability of built assets and resources (Hackitt, 2018). In fact, adoption of a traceability system relies heavily on the DR, in which an integrated system records automatically or manually potential traces and reuses them for future scenarios (Bechini et al., 2008). Such approach is holistically defined by Watson et al. (2019), proposing a DR framework (Figure 1.9) that connects all physical and digital traces of an asset across its lifecycle phases. While traceability resource units (TRU)s illustrated in this framework represent the relationship between physical and digital traces, the mechanism for linking of such traces is missing and needs to be clearly defined.

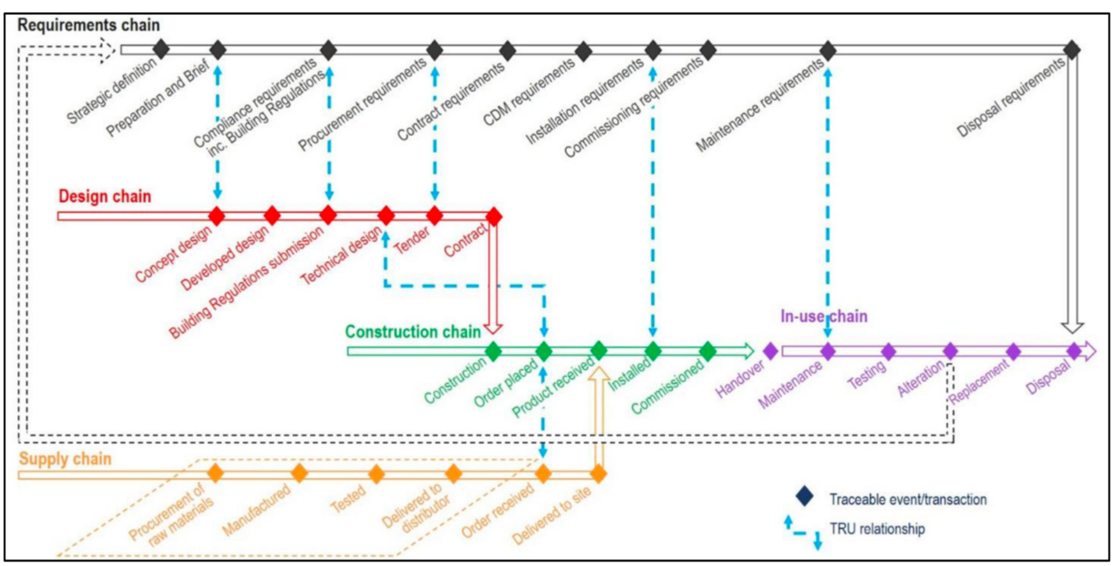


Figure 1.9 Framework for a digital record in construction
Taken from Watson et al. (2019)

## 1.6 Digital Thread (DTH)

By drawing attention to notation of traceability and the need to couple information generated from all stages of the asset lifecycle, recent studies have emphasized on the concept of Digital Thread (DTH) to support coupling of information (V. Singh & Willcox, 2018). Unlike other domains such as Product Lifecyle Management (PLM), a limited number of studies have investigated the concept of DTH in the AEC (Architecture, Environment, and Construction) sectors (Margaria & Schieweck, 2019).

Pang et al. (2021) defines DTH as “a data-driven architecture that links all information generated and stored within the DT enabling it to flow seamlessly through the entire PLM phase from invention to disposal”. From this definition it can be found that DTH contains all necessary information to link updates for a DT model. Such capability can provide holistic view of physical and digital assets across lifecycle stages by showing all the threads and their relationships (Figure 1.10).

To contextualize the concept of DTH in the LITE framework, DTH can link information generated from targeted purposes, physical/digital deliverables, and resources to their actual state. While information flows in forward and backward directions between the information milestones in the LITE framework, DTH is capable to unify and correlate heterogeneous physical and digital information in both directions across lifecycle stages.

This results in better monitoring, measurement and optimization of purposes, physical and digital deliverable, and resources such as material flow, waste elimination, transportation processes, logistics, etc. Controlling information flows coincides with the establishment of potential digital threads to facilitate this process by providing linked information for further verifications and validations.

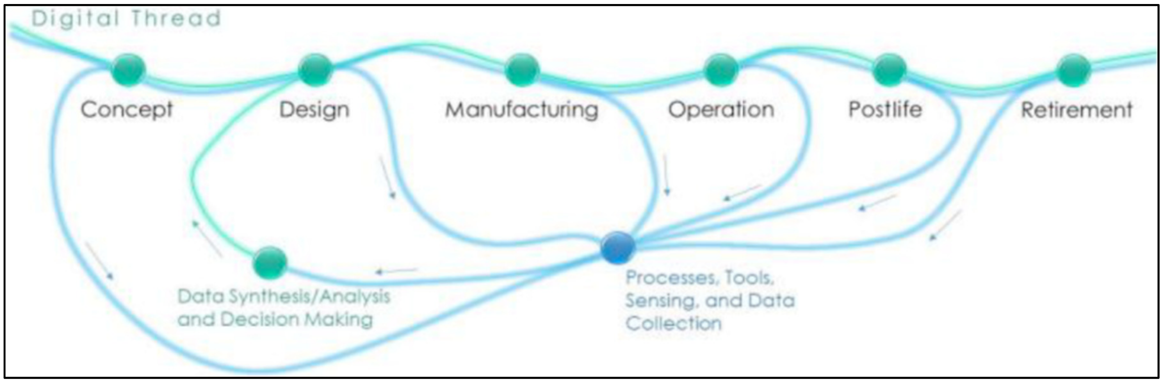


Figure 1.10 Multiple lifecycle stages into the Digital Thread
Taken from Singh & Willcox (2018)

From an enterprise perspective, organizations and companies will potentially be able to extract and aggregate data using a single enterprise digital thread independently yet linked to manufactures, contractors, engineering teams, architects, etc. This also contributes to timely access to data for better decision making and planning. Characterizing DTH under traceability principles can help overcome various barriers and challenges associated with transparency in supply chain, real-time data capturing, process visibility (e.g. logistic, transportation), decision making under uncertainty, and optimization of processes and assets across lifecycle phases (David et al., 2021).

Additionally, DTH can be deployed to quantify and operationalize sustainability principles (Heinrich & Lang, 2019), which include material data requirements, balancing industrial input and output, process chain analysis, resource management, and etc. While benefits are becoming evident, application of DTH requires a modular framework to define and contextualize key layers and dimensions of traceability in the built asset industry. Such framework could give broader insight for industrial users to track and measure circularity from multiple and heterogeneous perspectives.

## 1.7 Chapter Summary and Research Gaps

This chapter reviewed the principles of digital representation as well as the notation of asset and information coupling and its fundamental components. The LITE framework was introduced as a foundation to investigate further the characteristics, dimensions, and components of predefined couples. Moreover, the review of DT and information traceability revealed several barriers and potentials that can be addressed through the concept of asset and information coupling. In the following, some of the key research gaps are summarized based on the reviewed literatures.

### 1.7.1 Built Asset Lifecycle Information Coupling

The review of representation theories and coupling of physical and digital assets showed a lack of focus on basis of terms, definitions, concepts, and dimensions pertaining to lifecycle information coupling. As a nascent field of study, new constructs, mechanisms, and principles should be defined to take fully advantage of lifecycle information coupling. While the LITE framework has provided specific conceptual "Information Couples” and articulated them within an integrated model, the key mechanisms and practical implementation of information coupling across an asset’s lifecycle is missing and need to be further investigated and developed.

In addition, one of the limitations of the LITE framework has been information management of the existing assets and resources, particularly when they are close to their End-of-Life (EoL). This shortcoming makes information coupling difficult for the assets and resources planned for recovery or demolition. Therefore, comprehensive mechanisms and principles should be defined to support coupling of built asset and resources at any given information states and status.

### 1.7.2 Digital Twin in the Built Asset Industry

Regarding the concept of DT and related taxonomies, the lack of common definitions, metrics, and dimensions may lead to confusion and misunderstanding in the built asset industry, where digital twinning of the built assets and resources are increasingly receiving attention. The other gap is how to increase the tight coupling between the physical and the digital, aiming at higher representational fidelity and correspondence of DTs.

Finally, current DT lacks mature mechanisms to integrate multiple DT systems into a whole DT system, particularly in the case of complex systems with many parts and components. An integrated approach can potentially reduce the complexity of such systems and improve the robustness of the coupling between numerous DT systems across lifecycle of an asset.

### 1.7.3 Information Traceability in the Built Asset Industry

Within the context of the built asset industry, one of the major concerns has been inefficiencies in traceability of the built assets and resources. Without information coupling it would be difficult to link all the traces of assets and use them for decision makings. This can be particularly evident in the construction industry where a large number of traces pertaining to locations, product ID, product properties, and etc. are frequently missed, duplicated, or neglected across lifecycle stages. In addition a limited number of traceability standards and guidelines was reported as the main reasons for poor understanding of the notation of traceability in the context of built asset industry.

Moreover, the lack of integrated traceability methods and frameworks was highlighted as other barriers in implementing traceability. The literature also emphasised on the concepts of DR and DTH to record and link potential traces throughout of the asset’s lifecycle. The potentials of DTH enable tighter collaboration and communication between lifecycle actors for better provision and use of traces in the built asset industry by removing current interoperability barriers across the various interfaces, closing the information, digital and collaboration gaps.

Lastly, DTH facilitates continuous information flow in forward and backward direction across lifecycle stages. This is particularly evident in the LITE framework where multiple Information Gates are established to verify and validate information across asset's lifecycle. Potential threads can link all necessary physical and digital information to control information flows in forward and backward directions.

# CHAPTER 2

# RESEARCH METHODOLOGY

This chapter presents the chosen research methodology to address the research gaps identified in the previous chapter. Before introducing the research methodology, it is first necessary to review the research objectives and questions. This helps to set out better the research methodology and identify potentials avenues. Then, a detailed description of the chosen methodology and identified solutions are provided. Finally, the evaluation process of the research and presentation of the selected case studies are explained at the end of this chapter.

## 2.1 Research questions and objectives

Having outlined the problem statement in the introduction of this thesis, the research is used to form the answer to following fundamental research question:

Research Question (RQ): How can the concept of lifecycle information coupling of built assets and resources be characterized and framed to facilitate its adoption and implementation?

To address this research question, the research adopted methods and approaches to structure the body of knowledge from a theoretical and practical standpoint. To do so, taxonomical classification was identified as a potential approach to integrate existing definitions, terms, concepts, and theories found in the literature review. Providing a comprehensive taxonomy can play as a research artifact which can be used and referenced by stakeholders whose concern is lifecycle information coupling of built assets and resources. The one deserving attention here is that built asset lifecycle information coupling should not be limited to DTs of physical assets. As highlighted in the LITE framework (section 1.4.2), 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.

In light of the designed taxonomy, a Coupling Action instantiation framework was proposed to instantiate and enable application of coupling constructs, principles, and mechanisms in real world situations. Conceptualizing such an instantiation framework was carried out emphasizing on the activities and processes through which lifecycle Information Couples can be created and used. Further evaluation of Coupling Action instantiation framework was performed using two case studies to validate applicability, reliability, and accuracy of the instantiation framework in real-world situations and understand who could benefit from it.

Therefore, the objectives of this research can be summarized as follows:
Research Objective 01 (RO 01): To define the constructs, principles, and mechanisms needed to support the concept of lifecycle information coupling of built assets and resources in the built asset industry
Research Objective 02 (RO 02): To articulate these defined constructs, principles, and mechanisms within the taxonomy of lifecycle information coupling of built assets and resources.
Research Objective 03 (RO 03): To operationalize these defined constructs, principles, and mechanisms and enable their application in the built asset industry through a taxonomy and its instantiation framework.

## 2.2 The Design Science Research methodology

Design Science Research (DSR) was used as the main methodology of research to study, theorize, and investigate the concept of built asset lifecycle information coupling and its behaviour from an academic and industrial standpoint. The DSR methodology is a problem solving paradigm that focuses on the development and validation of artifacts (vom Brocke et al., 2020). Unlike natural science that attempts to understand reality, the DSR methodology creates new constructs, models, methods, and implementations for a particular purpose (March & Smith, 1995). Peffers et al. (2007) highlighted that DSR meet three main objectives: "(1) builds on prior research about design science in IS; (2) provides nominal process model enabling researchers to conduct DSR; and (3) provides mental model for researchers to evaluate and structure their design science outputs". Peffers et al. (2007) also identified six major activities through which a DRS methodology can be effectively applied. Each activity is summarized in Table 2.1.

Table 2.1 Design science research methodology activities
Taken from Peffers et al. (2007)

| Activity | Description |
|---|---|
| Activity 1: Problem identification and motivation. | Define the specific research problem and justify the value of a solution. |
| Activity 2: Define the objectives for a solution | Infer the objectives of a solution from the problem definition and knowledge of what is possible and feasible. |
| Activity 3: Design and development | Create the artifact. Such artifacts are potentially constructs, models, methods, or instantiations |
| Activity 4: Demonstration | Demonstrate the use of the artifact to solve one or more instances of the problem |
| Activity 5: Evaluation | Observe and measure how well the artifact supports a solution to the problem |
| Activity 6: Communication | Communicate the problem and its importance |

### 2.2.1 Implementation of Design Science Research Methodology

Based on the activities of DSR methodology proposed by Peffers et al. (2007), this study employs this approach to structure the required activities of the research project (Table 2.2). Each activity is linked to a specific knowledge base, which represents the materials (e.g. models, tools, and etc.) needed to accomplish the DSR.

Table 2.2 Activities of DSR methodology

| **Activity** | **Description** | **Knowledge base** |
|---|---|---|
| Activity 1: Problem identification and motivation. | Review of current literature revealed that the main dimensions and characteristics of lifecycle information coupling of built assets and resources are missing. This causes multiple coupling issues, and stakeholders would not be able to comprehend *what* and *how* information should be coupled across an asset's lifecycle. While the benefits of asset coupling are becoming evident, further research need to be carried out focusing on constructs, principles, and mechanisms of asset coupling that enable coupling of built asset and resources in the built asset industry. In addition, more study is needed to identify *who* would benefit from asset coupling and *where* people can apply that in practice. | Literature review of the previous studies that discuss current gaps and potentials in lifecycle information coupling of the built assets and resources. This covers books, articles, reports, and thesis projects that explore:<br>• Nature of digital representations.<br>• DT methods and principles.<br>• Coupling mechanisms, metrics, and enablers.<br>• Traceability of physical and digital built assets. |
| Activity 2: Define the objectives for a solution | • To identify a method for identifying the relationships and pattern among reviewed definitions, terms, concepts, frameworks, theories, and etc.<br>• To collect and analyse meaningful data from reviewed literatures.<br>• To identify the method for development of a taxonomy | • Coding system method by Edwards-Jones (2014).<br>• Qualitative data analysis of coded items with NVivo software.<br>• Taxonomy development method by Nickerson et al. (2013). |

| Activity | Description | Knowledge base |
|---|---|---|
| | • To develop an instantiation framework for evaluation of the taxonomy in real-world case studies. | |
| Activity 3: Design and development | Developing and representing the main dimensions and characteristics of the Built Asset Lifecycle information couples. Proposing a taxonomy to define seven high-level dimensions: Information Couples, Coupling States, Coupling Purposes, Coupling Outcomes, Coupling Actions, Coupling Metrics, and Coupling Enablers. Development of the Coupling Actions instantiation framework | • Components of LITE framework<br>• BIM Dictionary<br>• DT taxonomies,<br>• representational theories<br>• Circular Economy (CE) principles<br>• Traceability methods and frameworks. |
| Activity 4: Demonstration | Implementation of the Coupling Action instantiation framework to demonstrate how dimensions and characteristics of the taxonomy can be applied in real practices. | Dimensions and characteristics of the proposed taxonomy. |
| Activity 5: Evaluation | Implement DSR evaluation method to test and validate the designed artifact using two case studies:<br>• Thermal monitoring of a steel truss cantilever bridge.<br>• Development of a DT for a commercial office high rise building. | • DSR Evaluation framework by Pries-Heje et al. (2008).<br>• Extended version of the DSR Evaluation framework by Venable et al. (2012).<br>• Accessible databases (documents, models, reports, etc.) of the selected case studies. |
| Activity 6: Communication | Presentation of the developed taxonomy in CIBW78 international conference (2021) in Luxemburg (Davari et al., 2021). Presentation in | |

| Activity | Description | Knowledge base |
|---|---|---|
| | Symposium Innover Ensemble 2021 and 2022 | |

## 2.3 Data Collection

A variety of data collection methods were used to design and test the artifacts. The first round of data collection was carried out through an in-depth literature review on current trends, key challenges, and future potentials of built asset information coupling. For this, a collection of academic publications, industrial reports, thesis projects, and nonverbal documents (drawings, photographs, videos) was created to import and store the most relevant documents. The text documents and related issues in digital libraries are mostly gathered using online databases such as Scopus and Engineering Village. The collected literatures were mainly selected based on their topics, keywords, abstracts, disciplines, and citations. A wide range of input search terms were used for this process, such as:

- (“Digital Twin” OR “DT”) AND (“Lifecycle information management” OR “construction management,
- (“Asset Coupling” OR “Information Coupling”) AND (“Construction” OR “built environment”),
- (“digital representation theories” OR “representation”) AND (“simulation” OR “modeling),
- (“building information modelling” OR “BIM”) AND (“asset management” OR “project management”),
- (“taxonomy”) AND (“built environment”),
- (“ontologies”) AND (“information management”) AND (“Cyber-physical systems),
- (“Representation” OR “Functional”) AND (“Metric”) AND (“Information management”),
- (“Purpose” OR “Outcome”) AND (“Digital Twin) AND (“Simulation” OR “Representation”),

- (“Enablers” OR “Technology”) AND (“twinning” OR “coupling” OR “linking”) AND (“Information” OR “Data” OR “Asset”).

As data collection progressed, an open coding and classification framework was developed using NVivo software to filter and elicit themes from relevant documents in the literature. The second round of data collection was conducted during validation process by gathering and analyzing required data from various resources shared by partner organizations.

### 2.3.1 Identification of codes

The identification of codes is an interaction between the data and researchers which require continual assessment and rethinking on data (Edwards-Jones, 2014). A “code” is a representation of a phenomena or entity which can be founded in a text depending on research objectives and choice of methodology (Wuetherick, 2010). Initial coding was started by highlighting 160 academic publications and industrial reports in the various disciplines such as digital representation theories, lifecycle information management, information and communication technologies, circular economy, and etc.

The coded data ranged from purely descriptive to more conceptual themes. A common approach to identify a new code is starting with broad themes and then code them in details based on their importance and relevance to the topic (Lee & Fielding, 1996). In addition, Wuetherick (2010) suggested three main strategies to identify and name a code:

- Repetitions and regularities: identifying a repetitive phenomenon, idea, approach, or process across a range of experiences or studies.
- Posing questions: asking who, what, when, why, how, where, what if, and how much to ensure toughness and rationality of a coded data.
- Comparison of texts: comparing multiple texts containing similar code to analyze if a code makes sense to all of them.

As such, the first round of coding identification was performed with high-level themes and mentioned strategies. Accordingly, filed notes were added around the codes to facilitate retrieval of data for later use.

### 2.3.2 Hierarchical Coding

Given the large volume of coded data from various themes and concepts, a hierarchical approach was taken to define “Parent Codes” and “Child Codes”. The parent codes are those broad themes or concepts as mentioned in the previous section. On the other hand, child codes aggregate more detailed aspects of their parent codes, such as definitions, applications, capabilities, components, etc. These child codes should be regularly updated and revised based on the new findings.

To lay a meaningful coding foundation, parent and child codes were linked based on the specific properties, aspects, and features of each case. While parent codes represent a datum’s primary content and essence, child codes specify more detailed properties, attributes, features, or characteristics of a datum in a more descriptive way. The child codes were assigned to their parent codes based on data correspondence (they happen in relation to other activities or events), causation (one appears to cause another), frequency (they happen often or seldom), and sequence (they happen in certain order). Table 2.3 summarizes the hierarchy codes of reviewed themes and concepts and their relationships.

Table 2.3 The hierarchy codes of reviewed literatures

| Case | Parent Code | Child Code |
|---|---|---|
| Digital Twin | Applications | • Asset management<br>• Design & planning<br>• End-of-life<br>• Project management |
| | Architecture | • Physical component<br>• Digital component<br>• Data connection component |

| Case | Parent Code | Child Code |
|---|---|---|
| | Capabilities | • Monitoring<br>• Prediction<br>• Visualization<br>• Automation<br>• Assessment<br>• Clash detection<br>• Optimisation<br>• Others |
| | Categories | • Embedded DT<br>• Networked Twins<br>• Plain gadget mobiles |
| | Challenges | - |
| | Characteristics | • Communication<br>• Identifier<br>• Reflection<br>• Self-evolution<br>• Value driver |
| | Classes | • Products<br>• Systems<br>• Materials |
| | Components | • Connection<br>• Physical<br>• Digital |
| | Conceptual models | • Model-based<br>• Other |
| | Definitions | - |
| | Design phases | • Action<br>• Aggregation<br>• Analysis<br>• Communication<br>• Construction<br>• Insight |
| | Dimensions | • Conceptual element<br>• Data acquisition<br>• Data input<br>• Data link<br>• Data source<br>• Interface<br>• Purpose<br>• Synchronization |
| | Enabling technologies | - |

| Case | Parent Code | Child Code |
|---|---|---|
| | Use cases | - |
| | Levels | • Adaptive<br>• DTs<br>• Intelligent DTs<br>• Pre-DTs |
| | Purpose | - |
| | Potentials | - |
| Representation Theories | Digitalization | • Data<br>• Entity<br>• System<br>• Model<br>• Process<br>• Activity |
| | Simulation | • Deterministic<br>• Stochastic<br>• Static<br>• Dynamic<br>• Continues<br>• Discrete |
| | Representation | • Noise redaction<br>• Technologies<br>• Real<br>• Virtual<br>• Triangulating |
| | Modeling | • Model technologies<br>• Requirements<br>• Validity<br>• Construction<br>• Reuse<br>• Maintenance |
| | Purpose | - |
| | Challenges | - |
| | Enabling technologies | - |
| Asset Coupling | Purpose | - |
| | Types | • Intent Couple<br>• Physical Couple<br>• Digital Couple<br>• Asset Couple<br>• Deliverable Couple<br>• Resources & method couple |
| | State | - |

| Case | Parent Code | Child Code |
| --- | --- | --- |
| | Metrics | • Functional<br>• Representation |
| | Enabling technologies | • Software<br>• Hardware<br>• Network |
| | Outcome | • Value<br>• Performance<br>• Quality<br>• Safety<br>• Others |
| CPS | Component | • Physical<br>• Cyber<br>• Interface |
| | Challenges | - |
| | Definition | - |
| | Enabling technologies | - |
| | Framework | - |
| | Terms | • Embedded system<br>• Cloud computing<br>• System of systems<br>• M2M |
| Traceability | Definition | - |
| | Drivers | • Certifications<br>• Chain communication<br>• Welfare<br>• Quality<br>• Safety<br>• Others |
| | Granularity | - |
| | Enabling technologies | - |
| | Purpose | - |
| | Use case | - |
| | Challenges | - |
| | Methods | - |
| Digital Thread | Definition | - |
| | Challenges | - |
| | Application | • Operational<br>• Management<br>• Planning |
| | Framework | - |
| | Enabling technologies | - |
| | Methods | - |

| Case | Parent Code | Child Code |
|---|---|---|
| BIM | Purpose | • Design & planning<br>• Management<br>• Construction<br>• Operation<br>• Maintenance |
| | Simulation | • Entity<br>• System<br>• Activity<br>• Process |
| | Challenges | - |
| | Potentials | - |
| | Enabling technologies | - |

The hierarchical coding shown in Table 2.3 provided a number of advantages to meet the research objectives. Firstly, it made data analysis easier by coding of a specific term or phrase that was taken from broad themes, disciplines, and viewpoints. This facilitated in the taxonomical classification of widely used terms and phrases in the literature by harmonizing them into a high-level dimension or characteristic.

Secondly, the breadth of coded data from a large number of literatures allowed to trace the use of an idea from earliest documents to more recent ones. This helped in identifying the origin of a code and building new ideas upon previous efforts. Thirdly, breakdown of coded data into parent and child codes resulted in better interpretation of scales, granularities, or level of details within a set of data.

Such coding levels aided to establish a web of dimensions consisting of detailed coupling characteristics. Figure 2.1 presents the percentage coverage of coded cases by subject that are mutually exclusive. It can be found that a large portion of coded items are from DT, CE, asset coupling, and traceability studies.

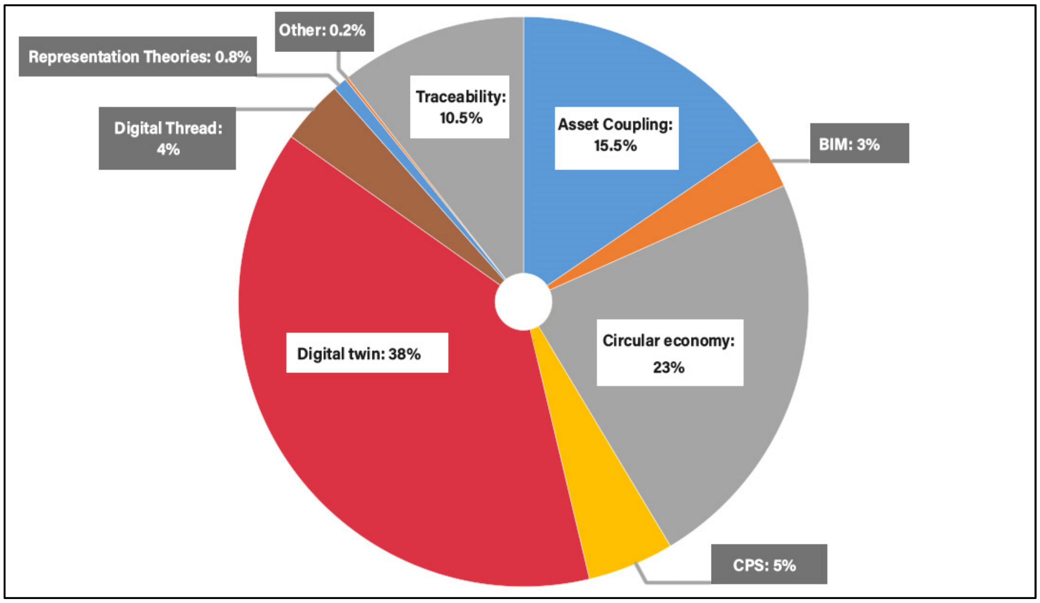


Figure 2.1 Percentage coverage of coded items by subject

## 2.4 Data Analysis

### 2.4.1 Coding Queries

After initial coding, queries in NVivo became important tools as they provided an integrated picture from the coded concepts, terms, definitions, etc. Given that the coded items were identified from different disciplines, queries mostly used to construct and explore data to answer unique questions arising in the data analysis.

| Word | Length | Count | Weighted Percentage | Similar Words |
|---|---|---|---|---|
| models | 6 | 1.242 | 2,18% | model, modelers, modeling, modelling, models |
| digital | 7 | 821 | 1,44% | digital, digitalization, digitization |
| product | 7 | 702 | 1,23% | product, production, productions, productivi... |
| systems | 7 | 636 | 1,12% | system, systems |
| physically | 10 | 593 | 1,04% | physic, physical, physically, physicals, physic... |
| information | 11 | 575 | 1,01% | information, informed |
| process | 7 | 508 | 0,89% | process, processed, processes, processing |
| simulations | 11 | 426 | 0,75% | simulate, simulated, simulates, simulating, si... |
| materials | 9 | 390 | 0,68% | material, materials |
| buildings | 9 | 320 | 0,56% | build, building, buildings, buildings', building... |
| construction | 12 | 289 | 0,51% | construct, constructed, constructing, constr... |

Figure 2.2 Word frequencies of the reviewed literatures

Three types of queries were used in NVivo: (i) word or phrase queries; (ii) theory-building queries; and (iii) administrative queries. Word or phrase queries were used to explore the words and their frequencies in the data. For example, Figure 2.2 shows some of the most frequent words identified from the coded data in the reviewed literatures.

To identify the inter-relationship among codes as presented in Figure 2.3, the theory-building queries such as "Matrix Coding Query" were used resulting in rich interpretation of the coded data from the literature. Matrix queries are also useful for comparative approaches in which overlapping among concepts, frameworks, and theories can be enclosed from the selected or all reviewed literatures. For instance, Figure 2.3 demonstrates several documents with the similar contents for the cases "Digital Twin" and "Asset Coupling". Matrix query allowed to segregate documents with overlapping in terms of cases and coded items. Such overlapping made data analysis easier by highlighting the relationship (e.g. similarities, differences, potentials) between coded items in a single document

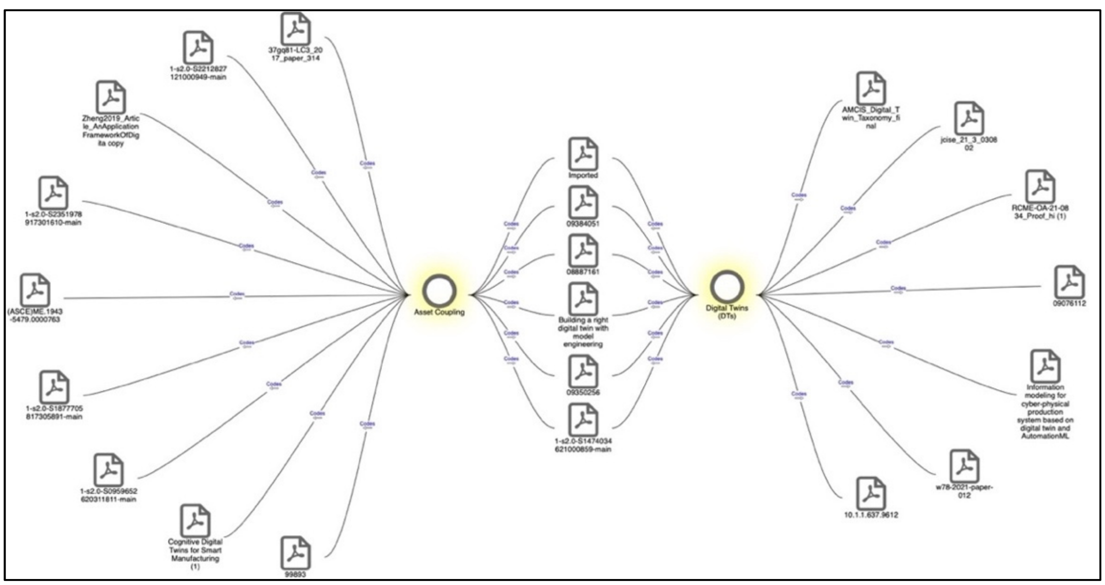


Figure 2.3 Identification of documents with similar cases and coded items

### 2.4.2 Cross-Code Analysis

To develop the deep understanding of coded data, multiple queries were performed using a different scope to see whether association holds only for some particular group of parent codes. Interpreting the pool of terms and phrases resulted from queries is a complex task. To facilitate this process, Edwards-Jones (2014) suggested that any result from research queries should be examined using the following simple questions:

- Is it true for everything / everyone?
- Does it depend on some other variables?

Given that dimensions and characteristics of built asset information coupling are not commonly grounded in the built asset industry, addressing the first mentioned question filtered many specific and contextualized data found in queries.
The dependency and independency of coded data was also analysed to identify the cause-and-effect relationships among query results. For example, the term “purpose” was commonly found in analyzed coded data and can be implied as an independent data which is applicable to any types of coupling activity. In contrast, the term “automation” depends on other variables such as “purpose” or “enabling technologies” that affect the automation of an object, system, or process.

The final interpretation of parent and child codes was performed in light of research problems by connecting findings in one or more existing theories. Well after interpreting the pattern and inter-relationships of coded data, all meaningful codes and subcodes were listed and finalised as illustrated in Table 2.3. While the final list of codes is rarely exclusive and definitive, it plays as an important foundation to refine and develop specific dimensions and characteristics for the built asset information coupling.

## 2.5 Development of a Taxonomy

Following the analysis of coded data, all meaningful codes and subcodes were adopted to present their patterns in ways that enable quick visual inspection. As mentioned in Section 1.1.4, one method to achieve this goal is taxonomical classification which organizes the body of knowledge into a hierarchical construct for further development and implementation (Wand et al., 1995). Following the activities of DSR methodology described in section 2.2, such taxonomy provides a foundation and offer new artifacts (Activity 3) for continuous development, extension, and refinement by domain researchers.

### 2.5.1 Taxonomy development Method

Development of a taxonomy is a complex task and requires systematic grouping of constructs, models, methods, and instantiations (March & Smith, 1995). Following the DSR methodology, Nickerson et al. (2013) proposed a method for developing taxonomies (Figure 2.4). The method entails the development of dimensions and their characteristics in response to the taxonomy's purpose. Nickerson et al. (2013) define the taxonomy's purpose as "meta-characteristic".

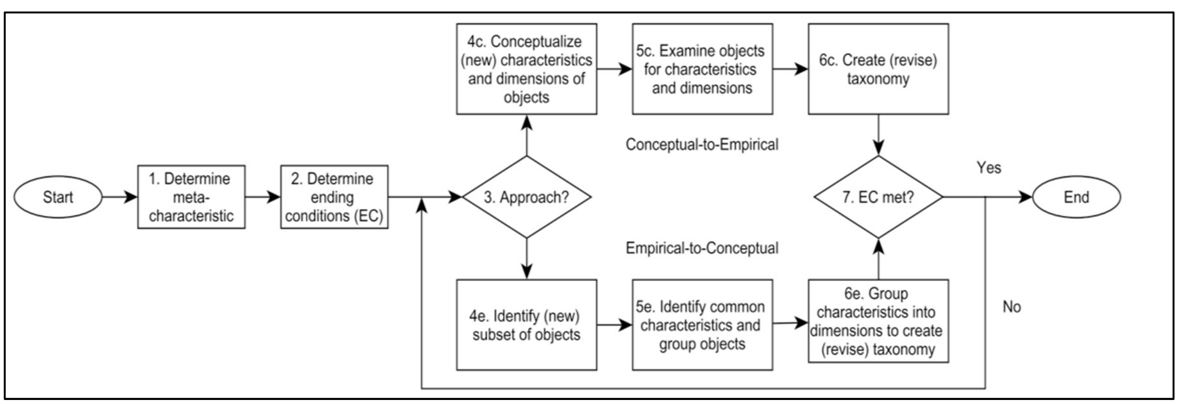


Figure 2.4 Taxonomy development method
Taken from Nickerson et al. (2013)

One must also consider “ending conditions”, determining if the taxonomy meets its preliminary purposes. Nickerson et al. (2013) listed 13 ending conditions which are either objective (e.g. no new dimensions were added, all dimensions were added) and subjective (e.g. concise, robust, comprehensive, extendible, explanatory).

Depending on the availability of data, the researcher may take an “empirical-to-conceptual” approach or a “conceptual-to-empirical” approach to develop the taxonomy. Due to the sparse and limited availability of data on the concept of built asset information coupling, this research adopts a "conceptual-to-empirical" methodology. This approach involves with conceptualizing the dimensions of the taxonomy based on the collected data and knowledge from the domain. Each dimension contains characteristics that must be examined after their conceptualization phase. After the creation of the overall layout of the taxonomy, continuous examinations take place to see whether any dimension need to be revised, removed, or added. Since research is constantly evolving, such examinations provide opportunities to keep the taxonomy up to date in case changes occur.

### 2.5.2 Conceptualization of Dimensions and Characteristics

As discussed in section 1.4.2, the LITE framework included six Information Couples representing the need to constantly keep physical and digital couples aligned and synchronised (Succar & Poirier, 2020). Having the main types of Information Couples, an in-depth analysis of the coded and classified items in NVivo was performed to further investigate and define the characteristics and dimensions of the presented couples.

Through an inductive process, all coded theories, models, definitions, terminologies, and frameworks were revisited to identify a pattern of relationships based on the reviewed data. To avoid ‘naïve empiricism’, which relies solely on all natural and empirical characteristics of the concepts and theories, this research proposed a taxonomy with eight high-level dimensions as follow: (i) Information Couples; (ii) Coupling States; (iii) Coupling Impacts; (iv) Coupling

Purposes; (v) Coupling Outcomes; (vi) Coupling Actions; (vii) Coupling Metrics; and (viii) Coupling Enablers.

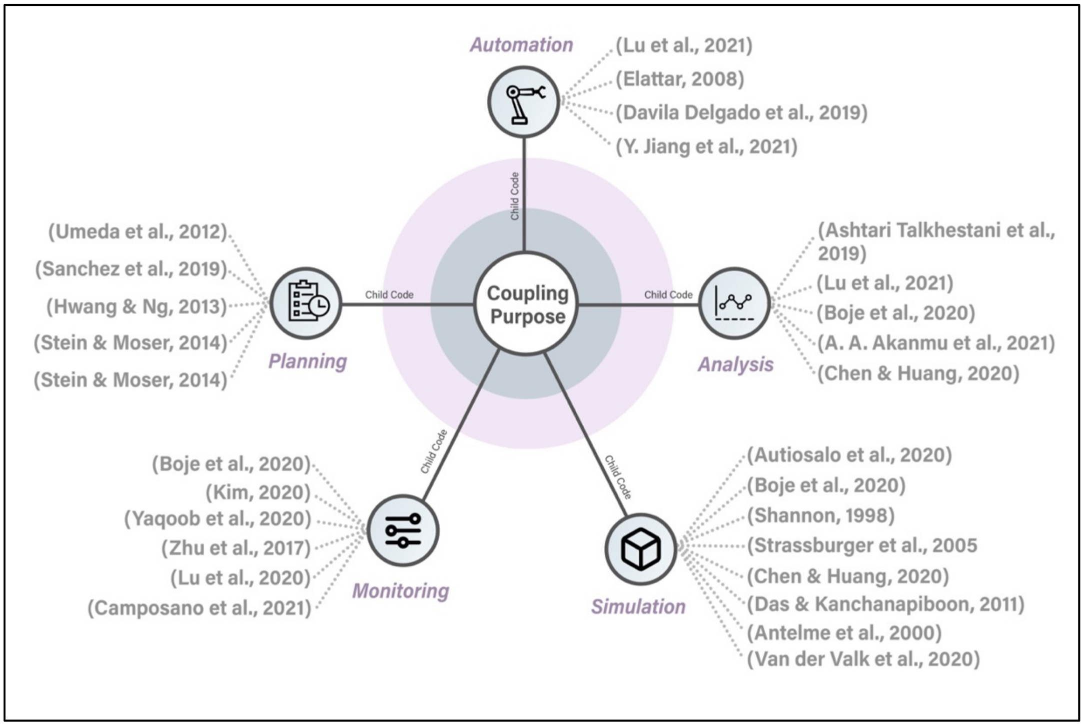


Figure 2.5 Overview of the dimension "Coupling Purpose" and its coded characteristics and references

As an example, Figure 2.5 represents the "Coupling Purpose" along with its characteristics (planning, analysis, simulations, etc.) derived from state-of-art. In the initial coding process, an extensive number of references were collected and coded for each dimension. Then, the list of references was narrowed down underlying key challenges and current trends of each characteristic. Figure 2.5 also shows the most relevant references for coupling purposes that were selected for the final coding foundation. Same procedure was carried out for other dimensions and their specific characteristics.

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The primary criteria to determine if a dimension or characteristic should be included in the taxonomy were based on the key challenges, current trends and future potentials of the reviewed theories and concepts presented in Chapter 1. In addition, comparative coding analysis in NVivo was performed to enclose overlapping and frequencies of the dimensions and characteristics across multiple literatures.

While coding of the existing literatures was consciously evolving over a sixteen month period, the transition from coding to construction of the key dimensions of the taxonomy was found as an important milestone. At this point, the result of comparative analysis enclosed a set of dimensions capable of covering various aspects of the asset coupling. The inter-relationships (e.g., cause and effect), clarity, comprehensiveness, unexclusiveness, and frequency of the findings from comparative analysis were considered to define them as the main dimensions of the taxonomy. While reviewed taxonomies in the literature (section 1.1.4) were ranged from very simple to complex, this research proposes a limited number of dimensions and characteristics which can be easily comprehended and expanded in future works. Further explanation of dimensions and their characterises will be presented in the next chapter.

## 2.6 Evaluation Process

Evaluation process (Activity 5) is a critical part of the DSR methodology and focuses on determining how well the proposed taxonomy performs in the built asset industry. This activity provides opportunities to review and revise the dimensions and characteristics of the built asset lifecycle information coupling taxonomy based on the findings from real-world case studies. The following sections explain implemented DRS evaluation framework, as well as selected methods and strategies for evaluating the proposed taxonomy and its instantiation.

### 2.6.1 DSR Evaluation Framework

Only a few studies have provided guidelines for evaluating an artefact in a DSR project. The most notable example is a DSR Evaluation Framework proposed by Pries-Heje et al. (2008), which proposes some guidelines and considerations through a 2-by-2 framework (Figure 2.6).

The DSR Evaluation framework includes two main dimensions that are contrasting naturalistic vs artificial evaluation, as well as ex ante vs ex post evaluation. Naturalistic evaluation emphasizes on evaluation of an artifact in a real environment, whereas artificial evaluation occurs in laboratory with simulations, unreal participants, and theoretical arguments. While ex post evaluation deals with instantiation of an artifact, ex ante evaluates an uninstantiated artifact (e.g. model, design).

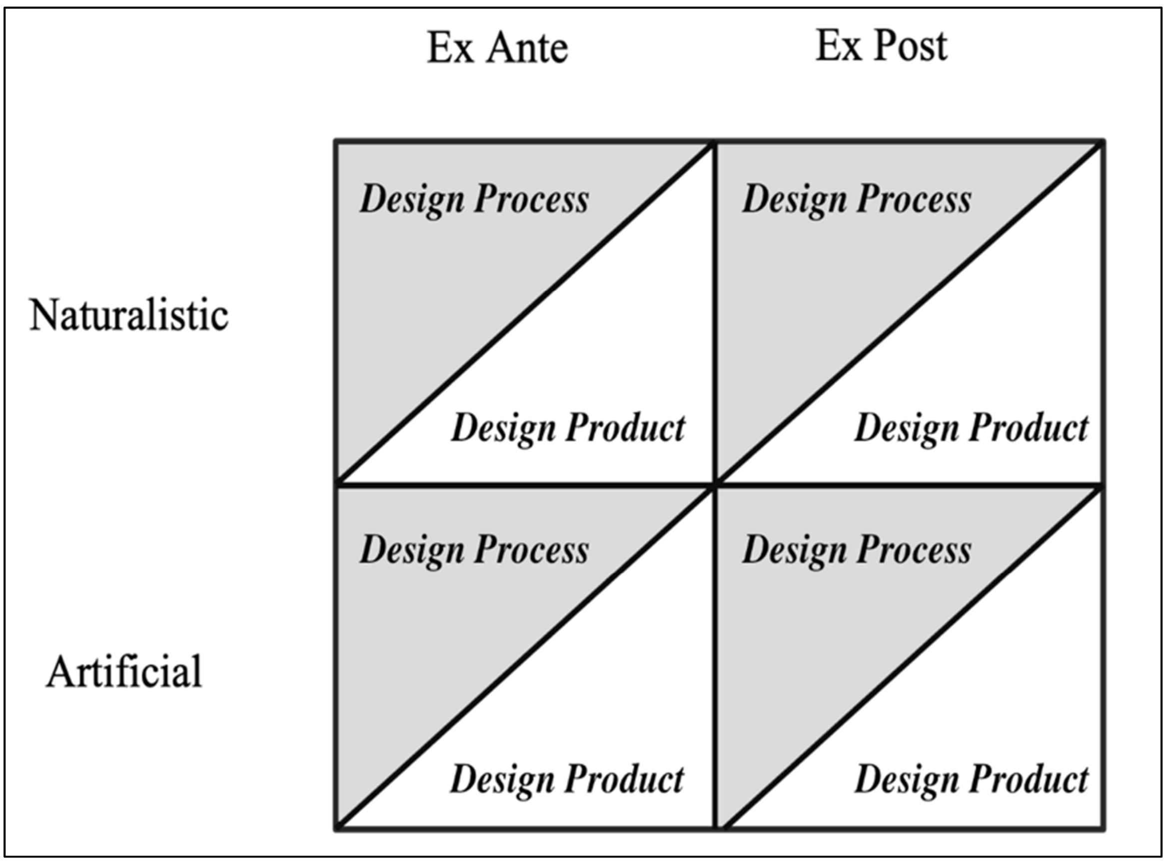


Figure 2.6 DSR Evaluation Framework
Taken from Pries-Heje et al. (2008)

Venable et al. (2012) extended dimensions of DSR evaluation framework and developed some strategies and methods to support a DSR artifact's evaluation. Figure 2.7 shows the extended version of DSR evaluation framework, underlying potential strategies for evaluating an artifact.

| **DSR Evaluation Strategy Selection Framework** | | **Ex Ante** | **Ex Post** |
|---|---|---|---|
| | | •Formative<br>•Lower build cost<br>•Faster<br>•Evaluate design, partial prototype, or full prototype<br>•Less risk to participants (during evaluation)<br>•Higher risk of false positive | •Summative<br>•Higher build cost<br>•Slower<br>•Evaluate instantiation<br>•Higher risk to participants (during evaluation)<br>•Lower risk of false positive |
| **Naturalistic** | •Many diverse stakeholders<br>•Substantial conflict<br>•Socio-technical artifacts<br>•Higher cost<br>•Longer time - slower<br>•Organizational access needed<br>•Artifact effectiveness evaluation<br>•Desired Rigor: "Proof of the Pudding"<br>•Higher risk to participants<br>•Lower risk of false positive – safety critical systems | •Real users, real problem, and somewhat unreal system<br>•Low-medium cost<br>•Medium speed<br>•Low risk to participants<br>•Higher risk of false positive | •Real users, real problem, and real system<br>•Highest Cost<br>•Highest risk to participants<br>•Best evaluation of effectiveness<br>•Identification of side effects<br>•Lowest risk of false positive – safety critical systems |
| **Artificial** | •Few similar stakeholders<br>•Little or no conflict<br>•Purely technical artifacts<br>•Lower cost<br>•Less time - faster<br>•Desired Rigor: Control of Variables<br>•Artifact efficacy evaluation<br>•Less risk during evaluation<br>•Higher risk of false positive | •Unreal Users, Problem, and/or System<br>•Lowest Cost<br>•Fastest<br>•Lowest risk to participants<br>•Highest risk of false positive re. effectiveness | •Real system, unreal problem and possibly unreal users<br>•Medium-high cost<br>•Medium speed<br>•Low-medium risk to participants |

Figure 2.7 A DSR evaluation strategy selection framework
Taken from Venable et al. (2012)

Regarding the evaluation methods, Venable et al. (2012) proposed a number of possible research methods as demonstrated in Figure 2.8. Depending on the nature of an artifact and available research resources, one or more of proposed methods can be implemented.

| DSR Evaluation Method Selection Framework | Ex Ante | Ex Post |
|---|---|---|
| Naturalistic | •Action Research<br>•Focus Group | •Action Research<br>•Case Study<br>•Focus Group<br>•Participant Observation<br>•Ethnography<br>•Phenomenology<br>•Survey (qualitative or quantitative) |
| Artificial | •Mathematical or Logical Proof<br>•Criteria-Based Evaluation<br>•Lab Experiment<br>•Computer Simulation | •Mathematical or Logical Proof<br>•Lab Experiment<br>•Role Playing Simulation<br>•Computer Simulation<br>•Field Experiment |

Figure 2.8 A DSR evaluation method selection framework
Taken from Venable et al. (2012)

Finally, the authors of this study proposed four-step DSR evaluation process as summarized in Table 2.4.

Table 2.4 DSR Evaluation Process
Taken from Venable et al. (2012)

| Process | Description |
|---|---|
| 1. Identify the context of evaluation | • What are evaluands? (e.g. models, concepts, etc.)<br>• Nature of the proposed artifact.<br>• What properties should be evaluated? |

| Process | Description |
|---|---|
| | • Goals and purposes of evaluation.<br>• Constrains in the research environment.<br>• What resources are available? (e.g. people, budget)<br>• How rigorous must the evaluation be? (Preliminary or detailed evaluation)<br>• Which aspects or properties are more important, less important, nice to have, and irrelevant. |
| 2. Match contextual factors | Match the needed contextual factors with one of the quadrants demonstrated in Figure 2.6 and Figure 2.7. |
| 3. Select evaluation method(s) | Select appropriate method(s) to evaluate the artifact. Examples of methods can be:<br>• Ex ante & naturalistic: action research, focus group.<br>• Ex ante & artificial: mathematical or logic proof, criteria-based evaluation, lab experiment, computer simulation.<br>• Ex post & naturalistic: action research, case study, participant observation, survey.<br>• Ex post & artificial: role playing simulation, lab experiment, computer simulation, field experiment, |
| 4. Design DSR evaluation | The specific detailed evaluations must be designed, e.g. design of surveys or experiments. This generally will follow the extant research methods literature. |

### 2.6.2 Implementation of DSR Evaluation Framework and Processes

Based on the dimensions of DSR Evaluation Framework, the evaluation of this research started with contextualization of the evaluation. The evaluands of this research were the taxonomy of built asset lifecycle information coupling (Ex Ante) as an uninstantiated artifact, and the

Coupling Action (Ex Post) as an instantiated artifact. For characterizing the nature of evaluands, the design artifacts can be either "design product" or "design process" (J. R. Venable, 2006; Gregor & Jones, 2007). The built asset lifecycle information coupling taxonomy is a design product which can be used to understand *what* coupling dimensions and characteristics should be considered to deliver a particular task. The Coupling Action can be considered as a design process, guiding stakeholders on *how* to couple information across an asset's lifecycle.

According to March & Smith (1995), the purpose of any DSR evaluation should be determined "whether or how well the developed evaluand achieves its purpose". The main purpose of proposed taxonomy is to provide the core elements, definitions and characteristics framing the physical-digital coupling of assets and resources in the built asset industry. The Coupling Action, as an instantiated artifact, is to provide necessary activities and principles through which Lifecyle Information Couples are created and maintained. The main purpose of DSR evaluation here was to determine the utility of the taxonomy and the Coupling Action in structuring the knowledge domain of lifecycle information management and enabling information coupling of physical and digital built assets and resources.

Next, evaluation of the designed artifact and its instantiation was established around four main competing goals:

- Efficacy: the ability and capacity of the built asset lifecycle information coupling taxonomy and Coupling Action to improve an expected or intended result in lifecycle information coupling of physical and digital worlds.
- Effectiveness: the ability and capacity of the built asset lifecycle information coupling taxonomy and Coupling Action to work in a real situation despite the possible organizational complications or constrains.
- Efficiency: the ability and capacity of the built asset lifecycle information coupling taxonomy and Coupling Action to work within resource constrains such as limitations in budget, people, time, equipment, and etc.

- Ethic: the ability and capacity of the built asset lifecycle information coupling taxonomy and Coupling Action to not put organizations, people, animals, technologies, and systems in danger or risk.

Regarding the evaluation methods and strategies, the proposed taxonomy was first evaluated by one industrial expert in terms of functionality, completeness, originality, quality, and usability. Several revision sessions were held to validate whether the proposed dimensions and characteristics are responsive to current coupling issues in theory and practise. The result of these revisions was published as two conference papers in order to obtain additional feedback from external reviewers all over the world. This preliminary ex ante evaluation was performed in artificial setting and provided valuable viewpoints and feedbacks on overall structure of the taxonomy as well as technical and functional aspects of defined dimensions and characteristics.

For the second round of evaluation, the case study approach was chosen as it provides opportunities to evaluate the design artifact in a real-world environment. The two projects selected for case study were in the same field, but they were different in terms of context, purpose, type, scale, and lifecycle state. Due to limited accessible resources (e.g. databases, site, people, time) in both projects, artificial setting was chosen as it provides “abstraction from the natural setting and is necessarily unreal” Venable et al. (2012).

To comply with the fourth process in Table 2.4, ex post evaluation was performed by designing an instantiation of the proposed taxonomy. As such, a detailed instantiation framework was developed, emphasizing on the main properties, activities, and datasets of Coupling Action. While the sheer volume of collected data from case studies was relatively large and heterogeneous, the instantiation framework served to comprehensively evaluate multiple aspects of built asset lifecycle information coupling.

## 2.7 Case Studies

The proposed taxonomy and its instantiation framework were evaluated using two case studies. The first case study took place during commissioning phase of a steel truss cantilever bridge and verified the efficiency of the coupling action instantiation framework as well as the effectiveness of its components. In this case study, the partner organization was the contractor. The second case study was performed during the planning phase of a DT implementation for a commercial office high rise building. In this case study, the partner organization was the owner. In this section, both cases studies are introduced along with their evaluation process. The results of evaluations are presented in Chapter 4.

### 2.7.1 Case study 01: thermal monitoring of a steel truss cantilever bridge

#### 2.7.1.1 Project Presentation: The Steel Truss Cantilever Bridge

This case study is a steel truss cantilever bridge spanning across two provinces. The bridge now provides the roadways for vehicles on the central lane and two side decks for the use of pedestrians and cyclist. Since 1946, the bridge has undergone several major rehabilitations such as truss replacement due to fire damage (1946), bearing replacement (1949), structural steel coating (1995), structural steel repairs (2016 – present). In April 2018, the government retained a number of contractors to provide an engineering proposal for the bridge's structural health monitoring and study a two-year thermal movement of the bridge.

Over the past few years, several inspections and studies have been taken and documented on the structural health monitoring of the bridge resulted in generation of multiple technical reports, drawings, guides, and etc. The structural health monitoring of the bridge is on-going and previous findings provided contractors is under further development. As of now, the findings of studies and assessment on structural movements, thermal behaviour of the bridge, and rehabilitation strategies have already been published and shared with various organizational or private databases. Such sources allowed this research to evaluate the proposed constructs in depth based on the previous findings and recommendations from stakeholders involved in this case study.

#### 2.7.1.2 Evaluation process of the bridge

Given that many organizations were involved in rehabilitation of the bridge for various purposes, this thesis considered the structural health monitoring of the bridge as the main purpose of lifecycle information coupling of built asset and resources. Although the partner organization provided necessary documentations and 2D/3D models from structural health monitoring of the bridge, most documents related to protocols, mandates, and guides of the project were not available or accessible at the time of evaluation. Nevertheless, this thesis adopted this case study to implement coupling action instantiation framework with existing documentations shared by partner organization. Figure 2.9 summarizes the steps taken to evaluate the coupling action instantiation framework using this case study.

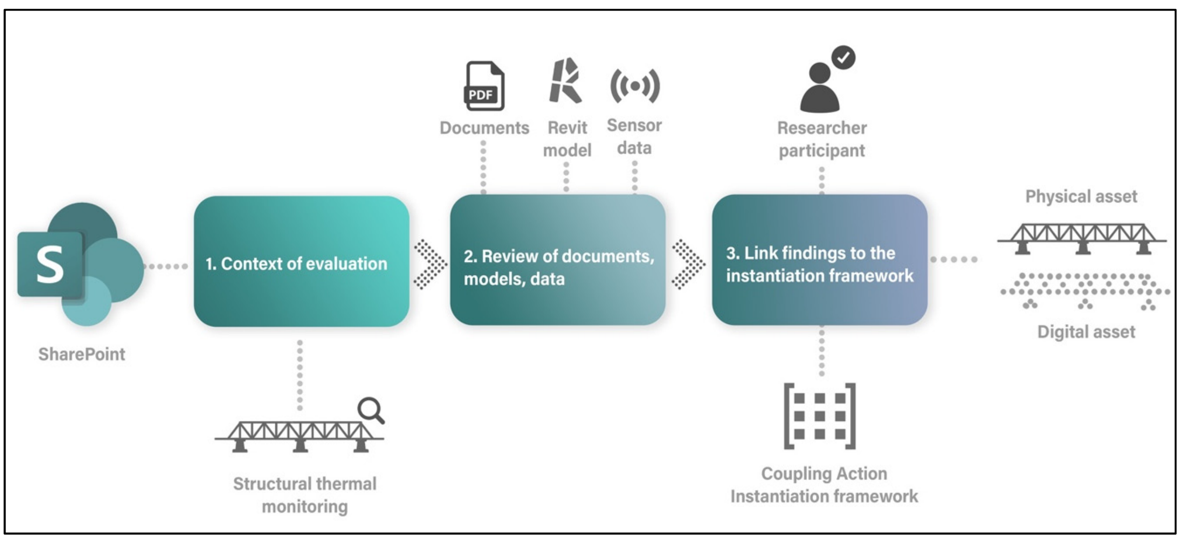


Figure 2.9 Evaluation process of the bridge

The first step was to identify the evaluation context, underlying goals and purpose of ex post evaluation. With structural health monitoring as the main purpose of asset coupling, the primary goal of this evaluation was to identify *what* potential data about structural monitoring of the existing bridge could be used for coupling actions. Another goal was evaluating *how* the instantiation framework can be implemented to couple physical and digital assets and resources of the project.

The second step was review of the documents and models provided by the partner organization. This step was necessary to identify the evaluands and properties of evaluation. Given that a large volume of technical data was reported into the documents, the main focus was on data pertaining to products (e.g. truss members, joints), site (e.g. geotechnical characteristics, urban connections), people (e.g. involved teams/groups, responsibilities, competencies), project (e.g. cost schedules, work breakdown structures), and equipment (e.g. sensors, hand tools, machine tools).

Moreover, the Revit model of the bridge was reviewed to compare modeled data (parameters, schedules, etc.) with specifications in structural technical reports. Regarding the real-time data from the physical asset, the bridge was facilitated with sensor devices providing data about thermal behaviour of the structural members over different periods of time. Such raw data were further reviewed to see how they can be implemented in coupling action.

In the last step, the coupling action instantiation framework was used to link reviewed data from PDF documents, Revit model, and sensor data Excel sheets. First, data taken from these sources were assigned to matrix of data categories (product, site, people, project, and equipment) and defined coupling actions in the framework. This process was further consulted and verified during multiple meetings with one of the involved researchers in the project. After two revisions with the participant researcher, the matrix of data categories and coupling action was completed based on the available and accessible data found in the SharePoint. Ultimately, cross-checking of data collected from the physical and digital built assets was carried out to verify if any additional data is required to improve the coupling action.

### 2.7.2 Case study 02: Implementation of a digital twin

#### 2.7.2.1 Project Presentation: Commercial Office High Rise building

The second case study is a commercial office high rise building owned by a real estate subsidiary company in Canada. Through subsidiary and partnership, the company seeks to optimise its operations by implementing a DT for the building. To achieve this goal, a number of strategic objectives have already established by GRIDD (Groupe de Recherche en Integration et Developpment Durable en Environnment Bâti) to diagnose current and desired situation of the complex as well as required digital technologies and methods to support operation and management of the high rise building.

Given that this is an on-going research project conducted by GRIDD, several diagnostic activities, planning, and pilot studies have been initiated to identify fundamental resources and skills supporting the project objectives. Implementation of a DT is expected to represent all physical activities of the building using sensor data from various sources and allow simulating of past and current states of the building elements for management purposes (organizational management, asset management, and facility management). The desired DT is also can respond to "what-if" questions and serve as repositories for BIM data for a wider range of building automation systems and sensor networks.

#### 2.7.2.2 Evaluation process of commercial office high rise building

Similar to first case study, evaluation process of the building was divided into three major steps (Figure 2.10). First, the context of evaluation was broadly identified as implementation of a DT of the building to optimise operation and management of the building. This includes potential solutions to meet the main vision of the company for digitalization of operation systems and management practices of the building over the next decades.

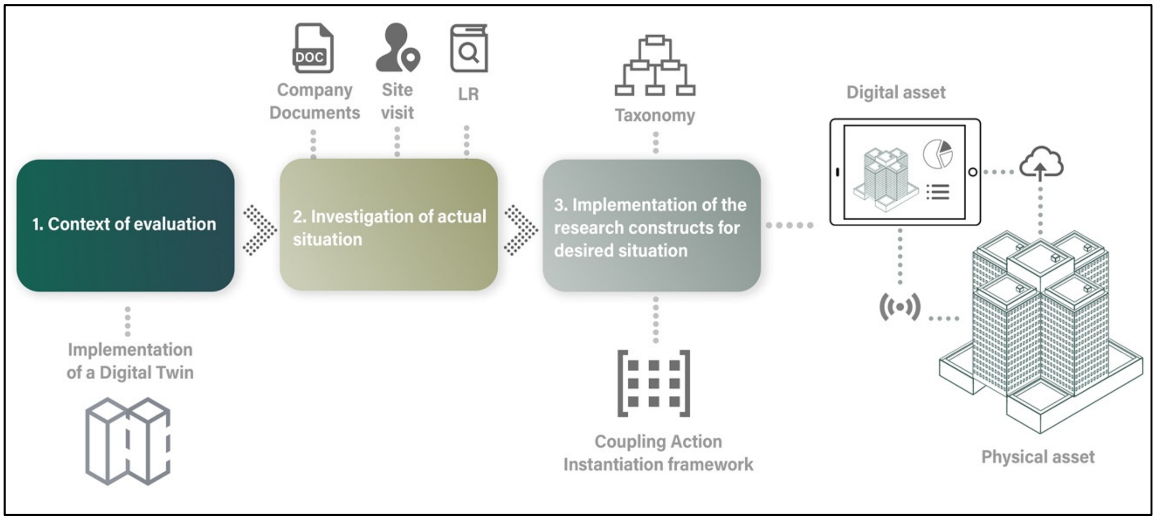


Figure 2.10 Evaluation process of the high rise building

In the second step, investigation of actual situation was performed. This process started with review of data sources shared by partner organization such as specifications of services and commitments, technical operation systems, the ecosystem of the building, strategic planning of the complex, and etc. Then, the review of similar practices at various scales was performed to identify their limitations and recommendations for development of a DT. These reviews aided in determining which parts of the proposed taxonomy and its instantiation framework could be more useful to support diagnostic and planning processes of a DT. Moreover, a number of site visits were scheduled to gain a better understanding of the actual situation of the building. This included identifying potential spaces/zones for monitoring and automation of management/operation systems, available technological solutions for asset management of the complex, and understanding the requirements of the partner organization for implementation of a DT.

In the last step, the proposed research constructs were implemented to evaluate how they can support various aspects of DT planning. For this, the proposed taxonomy was primarily evaluated to determine its effectiveness in identification of potential coupling purposes, coupling outcomes, and coupling actions of the case study. While the project still was at early phases of the development, a limited number of processed data were available to be used for evaluation of the coupling action instantiation framework. Therefore, evaluation was mostly performed using existing raw data and observation of the actual situation of the built asset.

## 2.8 Chapter Summery

This section introduced DSR as the research methodology, along with the activities and materials required to achieve the research objectives. An open coding and classification framework was developed using NVivo software to code relevant data (e.g. terms, definitions, concepts, theories, frameworks, models, and etc.) from the literature review. Further data analysis was performed on the coded data using coding queries and highlighting inter-relationships and dependencies among coded variables.

Taxonomical classification was found as the main research approach to organize all meaningful codes and subcodes found in data collection and analysis. The taxonomy development method proposed by Nickerson et al. (2013) was adopted to conceptualize necessary dimensions and characteristics for an integrated taxonomy. Through an inductive process, a taxonomy with eight high-level dimensions was conceptualized for further investigation of built asset lifecycle information coupling of physical and digital assets and resources.

The DSR evaluation framework by Pries-Heje et al. (2008) was used to structure the evaluation steps of the research artifact. The potential methods and strategies for evaluation process were also identified using the guidelines and dimensions of the DSR evaluation framework. Finally, the presentation of selected case studies was explained along with their specific evaluation process. The results of these evaluations are reported in Chapter 4.

# CHAPTER 3

# A TAXONOMY FOR BUILT ASSET LIFECYCLE INFORMATION COUPLING

Part of this chapter was published in the proceeding of 38th CIB W78 conference in October 2021.

## 3.1 The Need for a Taxonomy

As discussed in Chapter 1, the coupling of physical and digital built assets relies on common basis of terms, definitions, concepts, and dimensions pertaining to effective lifecycle information management. Taxonomies play a fundamental role in structuring a body of knowledge thus enabling researchers and practitioners to deal with complex scenarios and build new theories in the domain (Miller & Roth, 1994). However, taxonomical organization of knowledge in lifecycle information management is a common concern and most of the proposed taxonomies followed an ad-hoc approach (Nickerson et al., 2013). The LITE framework (section 1.4) highlights several gaps in such common approaches to effectively manage and process information throughout asset lifecycle. Therefore, a taxonomy which comprises key dimensions and characteristics of the built asset lifecycle information coupling is required to be created as an artifact of the research. The one deserving attention here is that built asset lifecycle information coupling should not be limited to DT of physical asset. The other five Information Couples deserve a more focused attention and will be served through the development of a taxonomy that detail all built asset lifecycle information couples along with their dimensions and characteristics.

## 3.2 Proposed Taxonomy for Built Asset Lifecycle Information Coupling

Representing the main dimensions and characteristics of Built Asset Lifecycle Information Couples, Figure 3.1 and Figure 3.2 show two levels of the proposed taxonomy including eight high-level dimensions: Information Couples, Coupling States, Coupling Impacts, Coupling Purposes, Coupling Outcomes, Coupling Actions, Coupling Metrics, and Coupling Enablers.

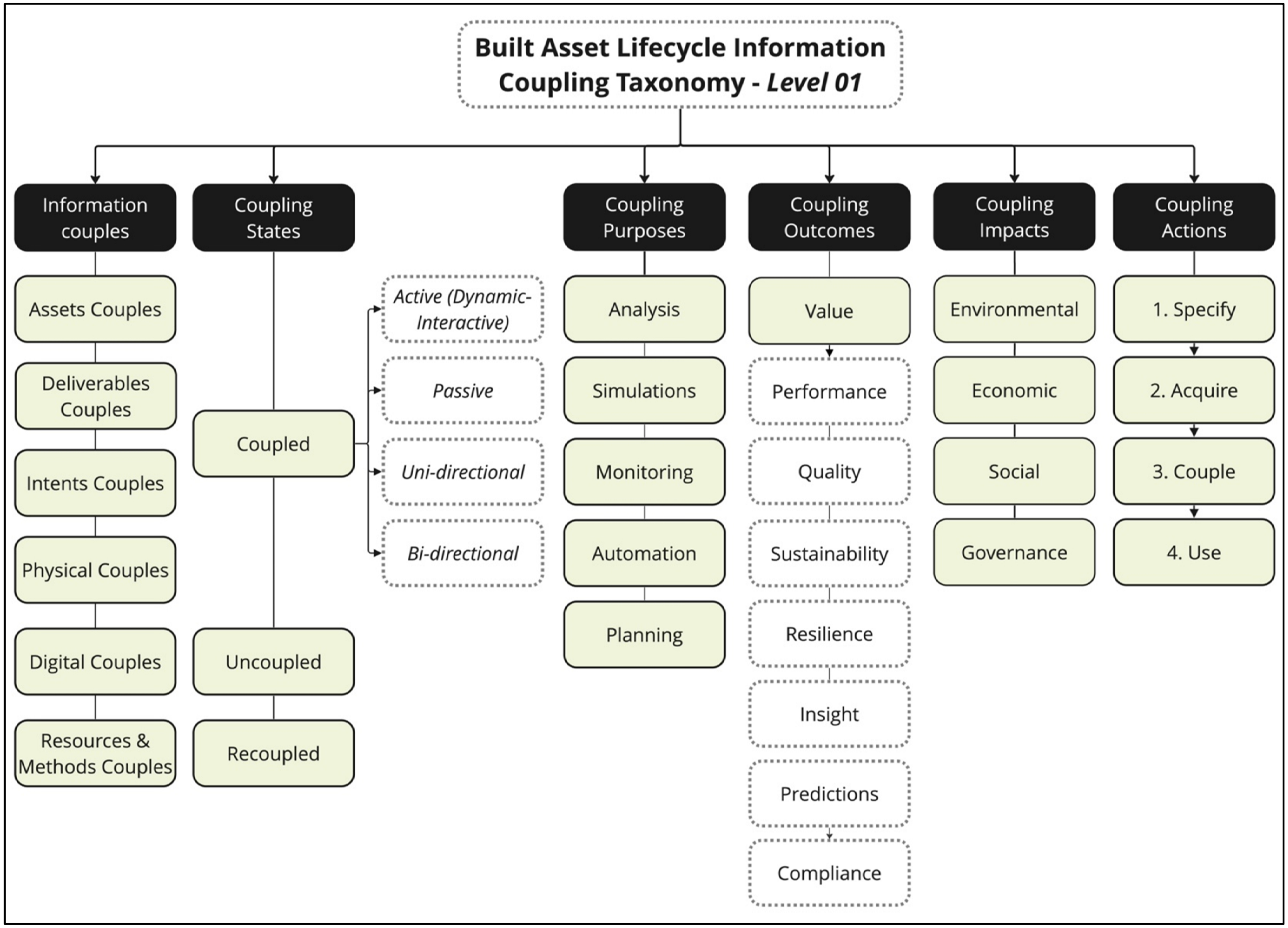


Figure 3.1 The Built Asset Lifecycle Information Coupling Taxonomy - Level 1

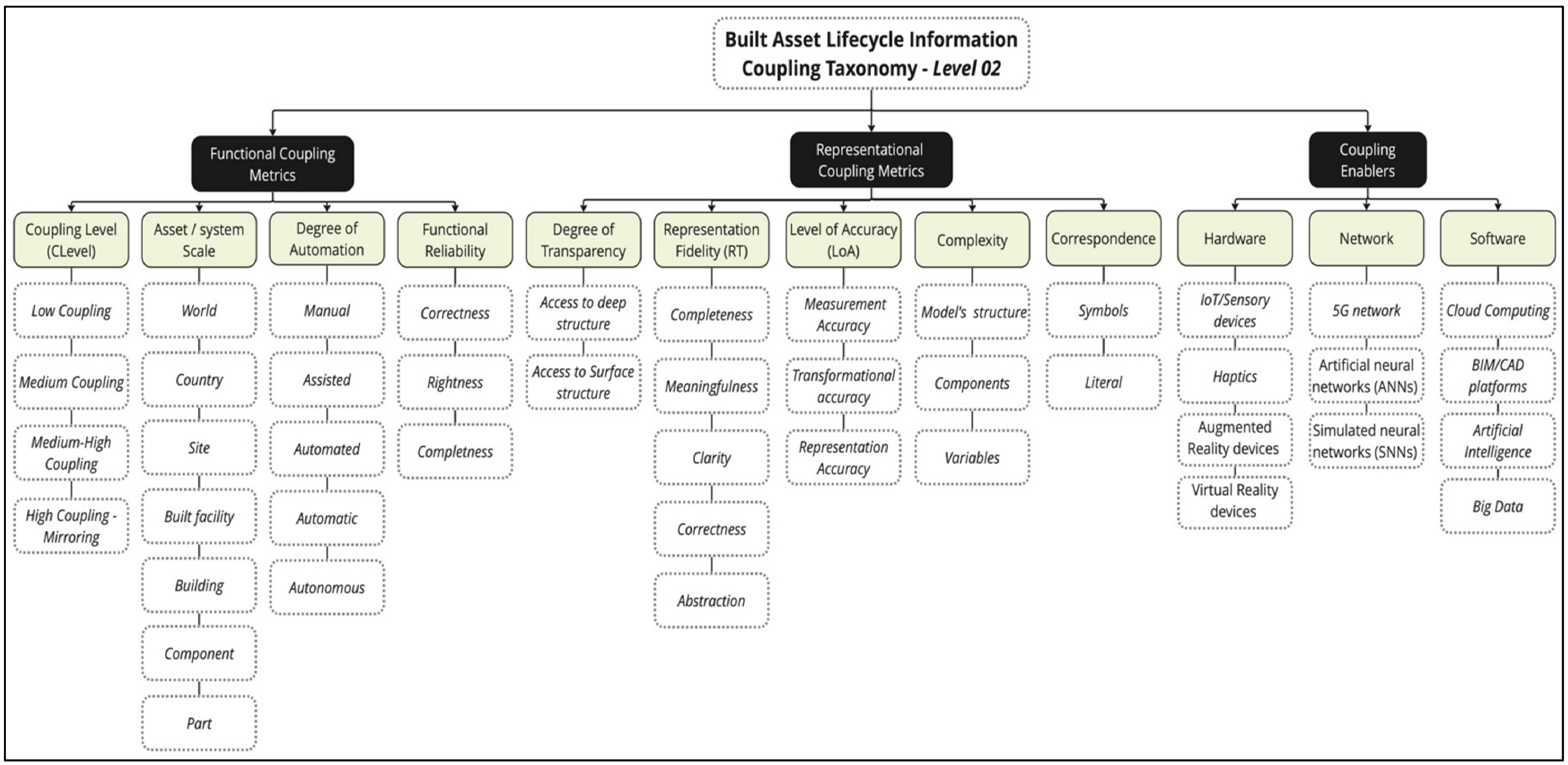


Figure 3.2 The Built Asset Lifecycle Information Coupling Taxonomy - Level 2

## 3.3 Meta-Characteristic

As mentioned in section 2.5.1, a meta-characteristic defines the main purpose to design and develop a taxonomy. In this research, the taxonomy's purpose (meta-characteristic) involves conceptualizing and determining the key dimensions and characteristics of built asset lifecycle information coupling to be expanded and implemented both in academia and industry.

While multiple dimensions have been identified for the taxonomy, they all serve as meta-characteristic and describe a particular feature of the built asset lifecycle information coupling. The meta-characteristic for the proposed taxonomy is expected to be used at different milestones of lifecycle information management as defined in the LITE framework. This encompasses intent to deliver new asset, expected/actual physical and digital deliverables, needed/available resources and methods, and intent to reuse existing assets. Depending on the purpose of each project, the users of the taxonomy can also decide which high-level dimension or characteristic should be considered to increase the lifecycle information coupling of built assets.

## 3.4 Dimensions and Characteristics

### 3.4.1 Information Couples

The first dimension is information Couples (Figure 3.3), referring to coupling types and 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: Intents Couple, Physical Couple, Digital Couple, and Recourses and

Methods Couple. These vertical Couples determine how well actual assets (e.g. available resources, physical/digital assets) achieve their predefined purposes (e.g. needed resources, physical/digital deliverables).

There are also two types of horizontal couples: Deliverables Couples and Assets Couple 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 DTs.

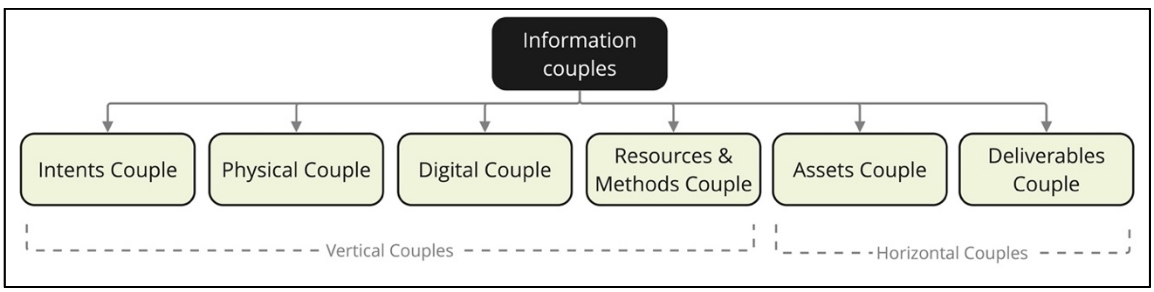


Figure 3.3 Information Couples

#### 3.4.1.1 Intents Couple

In current building practices, lack of information on the existing built assets and their EoL conditions have caused many inefficacies at different stages of lifecycle information management (Heinrich & Lang, 2019). When recovering or demolishing large built assets it is hard to remember all the links that were set to correlate information, and even impossible if multiple parties were involved in the project (Pinheiro, 2004).

Moreover, when a new asset is targeted to be delivered all historical information about previous practices might be needed for better decision making, construction error mitigations, cost and time reductions (Brandín & Abrishami, 2021). For example, one of the obstacles for delivering a new asset is obtaining information about reused materials or components (Chini & Bruening,

2003) such as amount or percentage of reused items, technical properties, process of recovery, new life expectancy, and etc. Such information can hardly be transformed into knowledge if no coupled as-built asset exists for acquiring relevant and reliable data (Reeves & Maple, 2019).

To address the issues mentioned above, Intents Couple was proposed to couple information between two Information Milestones in the LITE framework: (i) intent to deliver new assets; and (ii) intent to reuse existing assets. Depending on purpose of the project, Intents Couple becomes an inevitable part of lifecycle information management when information is required from existing as-built asset to recover it for future uses or to deliver a similar new asset. In addition, Intents Couple enables stakeholders to validate if existing assets suit predefined purposes and evaluating whether or not the asset can be recovered and reused (Succar & Poirier, 2020). This makes the Intents Couple more practical in the context of CE. Therefore, Intents Couple should be checked and referenced on a regular basis before making any decision about delivering or recovering an asset.

#### 3.4.1.2 Physical couple

Any physical asset includes spatial/geometric and functional attributes which need to be defined by professionals in a specific application domain (H. Zhang et al., 2020). These attributes are defined as physical deliverables underlying how assets are utilized or how they perform in actual environments (Succar, 2019). Validating whether physical assets meet their defined attributes requires continuous information synchronization between physical deliverables and actual physical asset. As projects progress, commissioning of actual physical asset may be challenging or even impossible due to lack of predefined attributes within the physical deliverables (Çimen, 2021).

This gap can be fulfilled by Physical Couple which provides users accessibility of information about defined attributes of physical assets. Given the tangible nature of physical asset, lifecycle information coupling of expected physical deliverables and actual physical asset can be facilitated through simple observation, continuous measurement, and monitoring of physical attributes (Boje et al., 2020). As noted, the importance of Physical Couple becomes more evident on project sites when delivered physical assets are subject to compliance checking, quality control, commissioning and etc.

#### 3.4.1.3 Digital Couple

Digital assets have shown unprecedented benefits in the built asset industry (Davila Delgado & Oyedele, 2021). Delivering a digital asset involves modeling of specific attributes that may enable delivery of a physical asset or may be part of an existing physical asset (Succar, 2009). Given that versatility of an actual digital asset heavily relies on its digital deliverables, the successful management of such process has been a concern due to the complex nature of digital representation (Sanchez et al., 2019). According to L. Zhang et al. (2021), this concern can be underpinned through comparative and integrated methods that verify what is defined as digital deliverables and what is built as digital asset.

The tight coupling between targeted digital deliverables (milestone 3) and actual digital assets (milestone 7) can potentially support any manipulation or verification of data used within digital artifacts (e.g. models, documents, data sets). Coupling of two milestones can also reduce a considerable amount of time and cost when detailed assessment of digital assets is required. For example, the time around clash detection of digital models can considerably be reduced by actively coordinating and coupling of defined digital deliverables (e.g. 3D geometry parameters or semantics in IFC files) and the actual digital model shared in the common data environment (CDE).

#### 3.4.1.4 Resources and Methods Couple

The built asset industry is one of the most resource-intensive industries (Becqué et al., 2016). Eliminating waste has remained a concern in lifecycle information management (Heinrich & Lang, 2019). This includes effective management of human resources (e.g. specialities and competencies) (Glass et al., 2012), equipment resources (e.g. available hardware, software, and network in the market) (Kusimo et al., 2019), financial resources (e.g. cash flow issues, getting loans) (Abdul-Rahman et al., 2011), and natural resources (e.g. materials, energy, water) (Bots & van Daalen, 2008). Optimisation of resource extraction requires innovative methods and mechanism to prevent the shortage of any type of resource.

Information coupling of “needed resources and methods” and “available resources and methods” can provide considerable insight for better management and optimization of resources at any scales. In practice, selection of resources requires real-time information about their availability, location, impacts, cost and etc. (Karlsen et al., 2013). Such information is constantly changing (Katenbayeva et al., 2016), and can hardly be traced without coupling of what resources and methods are *needed* and what resources and methods are actually *available*. Therefore, the importance of Resources and Methods Couple can be evident particularly when it comes to quantification of resource inputs and outputs, as well as resource impacts across lifecycle stages of physical and digital assets (Upstill-Goddard et al., 2015).

#### 3.4.1.5 Deliverables Couple

Deliverables Couple aims to couple “Expected Physical Deliverables” (milestone 2) and “Targeted Digital Deliverables” (milestone 3). The coupling of physical and digital deliverables occurs at “targeted” status of the LITE framework. Depending on the project purpose, physical and digital deliverables shape the project outcome and must be well defined at early stages of the project development (El Ghazi & Assar, 2008).

Before delivering of any actual physical and digital assets, coordination and integration of physical and digital deliverables may be neglected due to the heterogenicity of data (Lu, Parlikad, et al., 2020), changes in project strategies (Jenkin & Chan, 2010), or uncertainties in design parameters (V. Singh & Willcox, 2018). Poor alignment between expected physical deliverables with targeted digital deliverables may result in misinterpretation of project objectives (Jenkin & Chan, 2010) and failure to deliver actual physical and digital assets with the desired degree of completeness, accuracy, and reliability (L. Zhang et al., 2021). Deliverables Couple can provide planners and designers the opportunity to comprehensively review the targeted/expected attributes and variables of an asset at the very beginning of its lifecycle. This reduces possible mistakes or failures during the delivering of actual physical and digital assets.

#### 3.4.1.6 Assets Couple

Assets Couple is another horizontal couple defined at the “actual” status of the LITE framework. The asset coupling occurs when information transferred and exchanged between actual physical (milestone 7) and digital (milestone 6) built assets. An Asset Couple can be easily confused with the concept of DT. However, a DT can be regarded as a reformulation and instantiation of an Asset Couple for industrial practices. The notation of Assets Couple emphasizes on “actual” physical and digital built assets which are reached – through successful delivery of models, documents, and data sets – to be coupled and used until disposal. Whereas a DT can be served during design, construction, operation, and maintenance lifecycle phases.

To enable translation of changes from one asset to another, components or parts of the physical and digital built assets should be tightly coupled. Assets Couple uses digital models, documents, and data sets that mirror the behaviour of a physical asset across its lifecycle stages (Succar, 2019). Depending on the purpose of the project, various types of model-based simulation may be employed to create a digital couple of a something physical (Juarez et al., 2021). In addition, asset coupling should utilize highly granular representations to be able to visualize various physical or digital attributes (e.g. spatial/geometrics, resolutions, colors, textures, etc.) and functionalities that are defined in the project deliverables (Stojanovic, Vladeta, 2021).

While an ideal Asset Couple should be capable of transferring and exchanging data between physical and digital built assets in real-time and seamlessly (F. Jiang et al., 2021), the status of physical and digital built assets are most often updated in a near real-time manner particularly in actual practices in the built asset industry (Davari et al., 2022). Unlike common DT models and methods, Asset Couple should be able to continuously integrate multiple simulated digital models into a digital asset that represents an entire complex physical asset. Such capabilities can be further investigated from model engineering standpoint (L. Zhang et al., 2021), in which different modeling technologies (e.g. model constructions and evaluation) can be deployed to support real-time data transfer and integration between physical and digital built assets.

### 3.4.2 Coupling States

Coupling states represent the condition of a built asset lifecycle information couple. These couples can be Coupled, Uncoupled, and Recoupled (Figure 3.4). 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, recoupled, or uncoupled as the result of coordination between physical and digital built assets and resources.

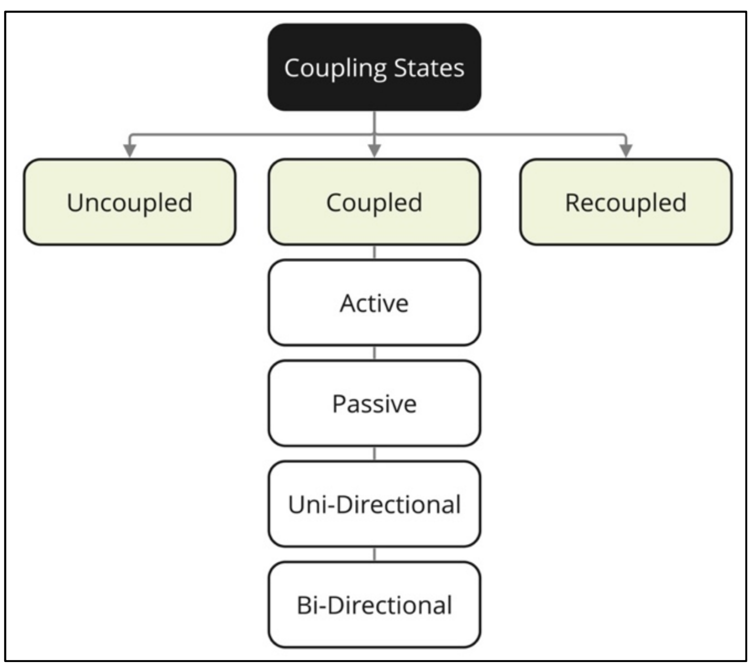


Figure 3.4 Coupling States

#### 3.4.2.1 Coupled

The “Coupled” states refers to a condition in which physical and digital assets and resources are highly dependent on each other, and any changes on one couple have an impact on the other. A coupled state includes four main characteristics: (i) Active; (ii) Passive; (iii) Uni-Directional; and (iv) Bi-Directional.

Active couples may indicate “live” or “dynamic” couples which actively transfers and exchanges data without pause, diversion or slack (De Roure et al., 2019). Active couples may evolve overtime (van der Valk et al., 2020), and adjust themselves under constant changes (J. Zhang et al., 2022). When a system generates or transfers a large amount of dynamic data, Active coupling is a preferred state for acquiring and processing of such data (Zhuang et al., 2021). For example, dynamic scheduling is one of the common methods to manage construction resources (You & Feng, 2020). Resources and Methods Couple may potentially support this process by actively coupling of the dynamic scheduling with just-in-time construction mode (Matsui, 2007), available resources on the site (Dittmann et al., 2021), changes in supply-chain (Sanchez et al., 2019), and etc.

Unlike Active couples, “Passive” couples denote Information Couples requiring specific triggers to instigate an action in a couple. An information couple in its passive form may need a direct exertion and authority of its user (Al-Azri, 2020). In some circumstances, a physical or digital couple can passively acquires and store granular data from its counterpart and makes it available to users as required (Madaan et al., 2018). Keeping the information couples in passive state could be useful when no real-time interaction is needed between assets and resources (Costin et al., 2014).

In addition, the connection between assets and resources, digital or physical, can be coupled either in one-direction or bi-directionally (Haße 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 CPS is an example of this (A. Akanmu & Anumba, 2015).

#### 3.4.2.2 Uncoupled

The “Uncoupled” state specifies the “loss” of connection between physical and digital assets. An uncoupled digital asset neither mirror nor match its physical counterpart (Østerlie & Monteiro, 2020). The correspondence between information couples is at the lowest level, and changes (e.g. a change in physical properties of a component in real space) in one asset can hardly be translated to uncoupled asset.

In an uncoupled state, users may experience difficulties to represent physical assets through virtual works, often defaulting to an incomplete and unreliable digital built asset (Burton-Jones, 2014). Digital information within an uncoupled state would be static and would not be updated according to real-time status of the physical asset (L. Zhang et al., 2021). The matter becomes more complicated when multi-disciplinary project teams generate disparate pieces of information that should be linked and integrated for better lifecycle management of planned/actual assets (Papadonikolaki, 2018). Indeed, it would be difficult to transform information within an uncoupled state into knowledge due to the high degree of fragmentation and heterogeneity in shared information (Boje et al., 2020).

To move from an uncoupled state to a coupled state, the coupling issues between assets and resources should be identified without making assumptions about interdependencies, and users should have enough time to find feasible solutions which address the coupling issues (Xiao et al., 2012). This process can be done during the “Recoupling” state which is described in the following section.

#### 3.4.2.3 Recoupled

The “Recoupled” state occurs when there is a need to rebuild the coordination and connectedness between built assets and resources (Zhou et al., 2022). In fact, recoupling is the consequence of uncoupling that includes actions required to reconnect all of the parts and components of something that was previously coupled (Horner, 2014).

Under recoupling, the uncoupled information and the new information may be rearranged and reorganized so that they will be ready to create a new coupled configuration (Covanich et al., 2008). To setup the recoupling state, recorded physical and digital assets and resources (e.g. documents, models, etc.) should be revisited and carefully revised by exploiting each user’s awareness and specific view (Smith & O’Brien, 1998). This helps to enclose hidden information about previous coupled or uncoupled state for further improvements and developments. Therefore, recoupling of assets and resources provides opportunities to control and review what information was previously coupled, as well as how new changes may affect an asset’s lifecycle.

### 3.4.3 Coupling Purposes

Coupling purposes are the reasons guiding the development and implementation of a built asset lifecycle information couple. These purposes (Figure 3.5) must be identified, from planning to maintenance phases of an asset. Amongst coupling purposes are planning, analysis, simulations, automation, and monitoring can all be supported by built asset information coupling to varying degrees. Although this list can be extended based on the various contexts, the present Coupling Purposes in the taxonomy are high-level and characterized according to a wide range of information uses in the built asset industry.

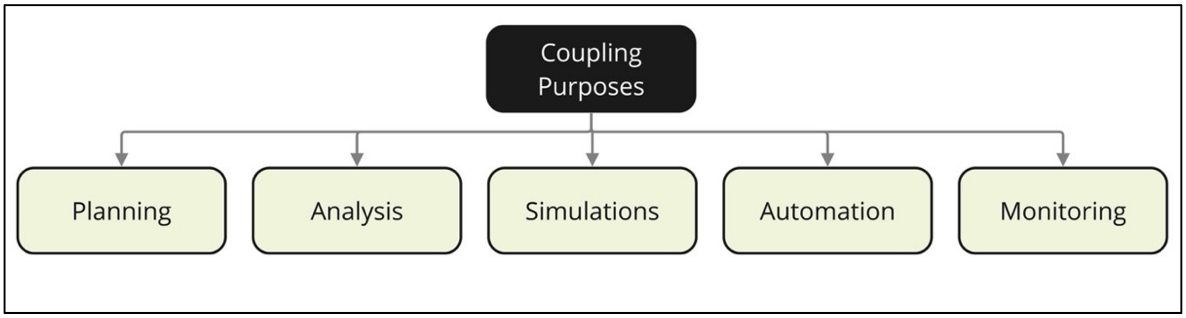


Figure 3.5 Coupling Purposes

#### 3.4.3.1 Planning

Planning is the process of thinking about potential strategies for managing assets and resources across lifecycle stages (Umeda et al., 2012). Planning is based on foresight to support not only a desired end result, but the steps needed to meet the objectives and goals of an asset. A plan usually prepared at the start of each project and details lifecycle stages in the design, construction, and maintenance of a physical or digital asset.

Numerous studies have been conducted for improving the planning process in the built asset industry (Sanchez et al., 2019). However, knowing where to get information, and how to exploit and interpret that information are still challenging in the planning process (Stein & Moser, 2014). Due to complex nature of the built asset industry, a valuable plan should underline relationships between each task and people involved in the project (Hwang & Ng, 2013). Indeed, identifying such relationships during the planning stage would be time-consuming and requires extensive efforts. In addition, reusing the existing knowledge is an integral part of any planning process that needs to be associated with integrated approaches.

Built asset information coupling is a potential solution to dynamically accumulate and maintain necessary information for planning purposes. Most often, planners may seek to similar practices along with their results in order to learn from them and reuse them for new planning activities. Through Information Couples, valuable information pertaining to current and past conditions of a similar practices can be easily recognised and reused to prevent duplication of work. Once historical information has been collected and interpreted for planning purposes, new information such as available resources and methods, defined requirements, existing regulations, milestones to reach within a defined timeframe, and etc. can be coupled with each activity or process specified by lifecycle planners.

Such information coupling improves the accuracy and achievability of lifecycle planning, while reducing negative impacts of the built assets on the environment, economy, and society. Moreover, relationships between the activities and processes can be better perceived by team members when assigned tasks are tightly coupled with information set. As a result, unexpected delays and cost overruns can be mitigated by coupling of resources and status of planned activities and process in a timely manner.

#### 3.4.3.2 Analysis

Analysing data is one of the common purposes to implement built asset information coupling. To effectively analyse data, scholars and practitioners have emphasised on the integrated methods using advanced analytical tools (Lu, Parlikad, et al., 2020). Built asset information coupling can integrate heterogeneous data sources and appropriate algorithms to conduct data analysis (Ashtari Talkhestani et al., 2019). While physical and digital built assets may transfer and exchange data in a real-time manner, dynamic data analysis through Information Couples can eliminate manual data processing (e.g. cleaning, structuring, correlating) (Boje et al., 2020).

Depending on analysis objectives, pieces of targeted data can be obtained from information couples and then be analyzed using statistical methods (e.g. regression analysis and dimension reduction), neural networks (e.g. self-organizing network and convolutional neural network), deep learning methods for identifying patterns, and visualization techniques (A. A. Akanmu et al., 2021). From an enterprise perspective, data analysis through built asset information coupling is beneficial to meet various needs of enterprises since every company or organizations has different preferences that should be integrated in a physical or digital built asset (Chen & Huang, 2020).

#### 3.4.3.3 Simulation

Simulation builds on other purposes and enables analysis, automation, predictions, and etc. (Autiosalo et al., 2020). The ability to simulate a model of a physical asset and conduct experiments with this model is one of the key purposes of built asset information coupling (Boje et al., 2020; Shannon, 1998). So far, various forms of asset coupling through simulations

| Feature | Characteristic | |
|---|---|---|
| **Temporal Parallelism** Temporal parallelism between simulation and visualization | **Concurrent** Simulation and visualization run temporally parallel | **Post-run** Visualization runs temporally after the simulation |
| **Interaction** Interactions between simulation and visualization | **Bidirectional** Simulation and visualization each react to the other tool's commands | **Unidirectional** Only visualization reacts to the simulation's commands |
| **Hardware Platform** Hardware platforms on which the simulation and the visualization operate | **Monolithic/ Homogeneous** Simulation and visualization run on one platform | **Distributed** Simulation and visualization operate on different hardware platforms |
| **Visualization Tool Autonomy** | **Integrated** Visualization tool is integrated in the simulation tool | **External** Visualization tool works independent of the simulation tool |

Figure 3.6 Forms of coupling simulations and their characteristics

Taken from Strassburger et al. (2005)

have been defined by scholars (Figure 3.6), including temporal parallelism, interaction, hardware, visualization tool autonomy (Strassburger et al., 2005).

Based on the project objectives, model-based simulations may need to be developed as digital deliverables from scratch, or they may already be developed and require further adjustments. In either case, information coupling of as-targeted and as-built assets can potentially reduce the time and efforts in model construction (Chen & Huang, 2020), model evaluation (Das & Kanchanapiboon, 2011), and model reuse (Antelme et al., 2000) across asset's lifecycle. With respect to time, Information Couples have great capacity to deal with continuous and discrete event simulations (Van der Valk et al., 2020). In fact, model-based simulations are constantly under changes and defined information couples can dynamically acquire, process, reuse and maintain model inputs and outputs at different information milestones.

#### 3.4.3.4 Automation

Implementing automated approaches to deliver physical and digital built assets is becoming increasingly important in the built asset industry. Slow adoption of automated technologies in the built asset industry has resulted in many inefficiencies in lifecycle information management of assets and resources (Lu et al., 2021). From project management's viewpoint, it is always difficult to keep a holistic sight on the information circulating within as-targeted and as-built Information Milestones (Elattar, 2008).

Robotics and automated systems have demonstrated their value in asset production, operation, and maintenance (Davila Delgado et al., 2019). However, any automation requires integrated methods and constructs to deploy a large volume of data within the information cycles. Information Couples can potentially be associated with robots and automated system to minimise the manual works that needed to extract and process data from each information cycle. Moreover, the use of data mining or ML techniques allow Information Couples to automatically learn from historical data and visualize their findings (e.g. structure and properties of built assets) with high degree of fidelity and accuracy (Y. Jiang et al., 2021).

#### 3.4.3.5 Monitoring

Asset monitoring involves tracking of physical assets using advanced hardware, network, and software solutions. IoT devices are the most common monitoring solutions that sense continuous data influx and transmit it to machines or systems with an interpretable format (Boje et al., 2020). Despite successful technological advancements in asset monitoring, a number of challenges remain to be addressed such as ensuing sufficient asset visibility (Yaqoob et al., 2020), tracking multiple physical and digital objects (J. Kim, 2020), understating exactly what problem should be solved after monitoring process (Zhu et al., 2017), detection of anomalies due to the high degree of system complexity and number of components within an integrated system (L, Xie et al., 2020).

The concept of asset coupling is envisioned to keep various parts of a monitored physical asset in alignment. This can be done through coupling of physical objects and their digital replica to analyze the status of information before and after monitoring. Without lifecycle information coupling, stakeholders may find it difficult to structure and interpret real-time data and link them to their knowledge databases for making effective decisions.

A tight coupling between physical and digital assets allows stakeholders to immediately access monitored physical data on the virtual side at any time and under any conditions. This results in data transparency (Camposano et al., 2021), real-time visualization of monitored data (e.g. graphs, simulations, tables), easy accessibility of monitored data, and issuing immediate warnings to workers in case of risk or danger (Boje et al., 2020).

### 3.4.4 Coupling Outcomes

Coupling outcomes are the expected effects of coupling actions for specific purposes under specific conditions. These outcomes can be, among others, value generation in terms of quality improvement, obtaining insight, sustainability, resilience, performance, prediction, and compliance of an asset or resource. Physical and digital assets may be coupled to achieve such outcomes as depicted in the Figure 3.7. Similar to Coupling Purposes, the list can be extended with a wide range of detailed outcomes. Nevertheless, defined outcomes are high-level and can be integrated as the outcomes of a single coupling action.

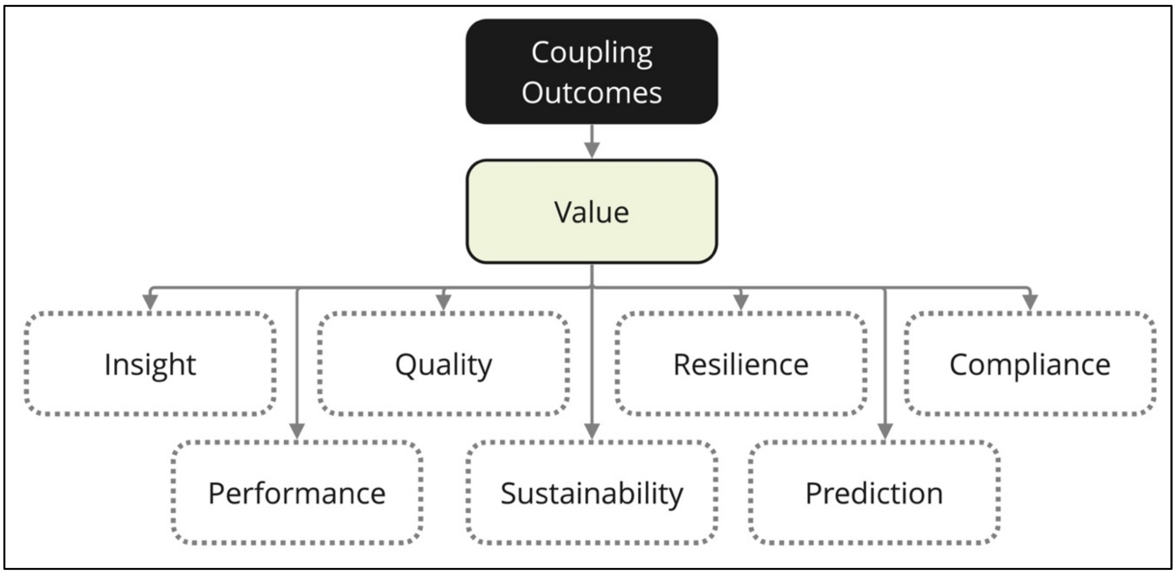


Figure 3.7 Coupling Outcomes

### 3.4.4.1 Value

Value is an overarching outcome which can be characterised by insight, quality, resilience, compliance, performance, sustainability, and prediction. In general, value means what the client "wants" and what he/she is ready to pay for it (Womack & Jones, 2008). It can be generated as the result of interactions between the supplier and the client (Koskela, 1992). In the built asset industry, value may change with time based on the different project objectives or attributes (CDBB, 2020). Yet, Information Couples may derive value not only through the coupling of as-targeted and as-built information generated by suppliers and clients, but also from innovative ways to combine and reuse coupled information for future implementations (Camposano et al., 2021).

From business perspective, the characterization of asset coupling values in the built asset industry, Oracle (2017) listed a number of potential values as follows:

- Risk assessment and safety: Coupling of digital built asset with their physical counterparts can enable "what-if" scenarios to assess potential risks identify mitigation strategies across an asset's lifecycle stages.
- Remote monitoring and control: information couples allow stakeholders to monitor physical and digital built asset anywhere and control them through feedback mechanisms.
- Better inter-team synergies and collaboration: with information at a fingertip, project teams can save time to better collaborate with each other resulting in greater asset's productivity.
- Personalization of assets and services: having the detailed historic information through couples, stakeholders can better track the market needs and trends leading to faster and smoother gear shifts under future customer needs.
- Better documentation and communication: having the readily available information coupled with digital and physical built assets keeps stakeholders well-informed and increases the project transparency.

In the context of this research, value can be achieved through a prescribed coupling process with analytical focus on various components of an asset to minimize their negative impacts on economy, environment, social, and governance aspects. Based on the coupling purpose, value can be manipulated by improving one or more sub-characteristics (insight, quality, performance, etc.). Each sub-characteristic of the value is explained in the following sections.

#### 3.4.4.2 Insight

Built asset information coupling provides the capacity to gain greater insight into performance across asset's lifecycle (Camposano et al., 2021). Having the coupled information at different phases of an asset can enable stakeholders to pull out any required data and get insight from relationships or hidden patterns among raw data (Ali, 2020). These patterns may lay the foundation to make informed decisions and implement actions by stakeholders (Pang et al., 2021).

While visualization is a common requirement for the built asset information coupling, the gathered insights can be presented using visualization tools which highlights the patterns between physical and digital built assets and resources (Yaqoob et al., 2020). For example, one of the common challenges in lifecycle information management is understanding if parties are working at, over, or under their capacity (Guzzetti et al., 2020). In this case, coupled information about active working hours, competencies, and inter-dependencies at different milestones can provide valuable visual insights for team principles or managers to keep their team members at capacity.

#### 3.4.4.3 Performance

Built asset information coupling is a promising solution to improve the performance of physical and digital built assets over their lifecycle phases. Information Couples can potentially disclose the key variables and attributes of an asset and provide the means to improve its performance under different physical or environmental conditions such as tensile strength of a concrete column under live loads with respect to its defined structural codes, or performance of an air-conditioning equipment to maintain the ambient temperature and moisture level of a room in accordance with its defined geometric/spatial features (Yaqoob et al., 2020).

For the digital built assets, performance can be significantly improved when model-based simulations (e.g. BIM models) are tightly coupled with their physical counterparts. For example, increasing the model's performance in processing and recording a large volume of data acquired from a physical asset, or visualizing the behaviour of a physical asset in a real-time manner with high expressivity (Juarez et al., 2021).

#### 3.4.4.4 Quality

Asset quality in the built asset industry can be defined as "how well an asset satisfies customer needs, serves its purpose and meets industry standards" (Jraisat et al., 2016). Organizations use a wide range of procedures and processes to ensure quality of their assets (Dahlgaard-Park et al., 2018). Quality development stages includes quality control, quality assurance, quality management, total quality management (TQM), and sustainable quality management (SQM).

Regardless of differences between these and other approaches, the built asset industry – particularly in the context of industry 4.0 – has been associated with challenges in quality management of the built assets. ISO 9001 (Fonseca & Domingues, 2016) has highlighted some of the challenges such as determining the needs and expectation of customers, determining appropriate resources to meet quality objectives of the assets, establishing innovative processes to ensure continuous improvement of asset quality, applying integrated solutions to prevent nonconformities and eliminating causes, and etc.

To address such challenges, Foidl & Felderer (2016) emphasized the monitoring of physical processes and activities within smart factories ("a Factory that context-aware assists people and machines in execution of their tasks") through the virtual copy of physical world and make decentralized decisions. Continuous monitoring of the physical world through Information Couples is one of the common requirement of asset coupling (Fonseca & Domingues, 2016). Stakeholders may use Information Couples as "smart activity tracker" that monitor all quality testing or assessment steps and delivery notes. Furthermore, feedbacks and complaints regarding asset quality can be handled much faster and in details by checking the coupled parameters and attributes of physical and digital built assets (Foidl & Felderer, 2016). To support this, Information Couples can support comparison between "quality pre-sets" requirements and physical asset's status/condition. This also allows suppliers to diagnose quality issues with an asset before delivering it to users.

#### 3.4.4.5 Predictions

Besides coupling of past or current states of the asset, future courses of actions can be predicted using Information Couples (Camposano et al., 2021). Predicting future states of assets and resources highly depends on the measured values of data inputs and outputs as well as initial coupling of asset deliverables (Boje et al., 2020). In addition, active predictive simulations and use of immediate actuators on the physical built assets play important roles to facilitate prediction process with high fidelity (Tomko & Winter, 2019).

Information Couples are ideal to harmonize dispersed data at Information Milestones and predictively optimise them by incorporating simulation models or ML features. Depending on the prediction objectives, meaningful coupled information provides predictors a great capacity to forecast various aspects of built assets and resources and leads to a better management of lifecycle information.

#### 3.4.4.6 Sustainability

Sustainability outcome can be achieved in terms of economic development, social development, and environmental development (L.-Y. Shen et al., 2007). To move towards a true sustainable outcome, combination of advanced technologies and built asset lifecycle information coupling can help stakeholders optimise sustainable solutions at each stage of development. Numerous methodologies and indicators have been proposed across domains to assess sustainability of the built assets. To incorporate such methods and indicators with lifecycle information management, the availability of coupled information is critical across asset lifecycles. For instance, sustainable choices in building material requires coupled information about its availability in the market, natural properties, or possible risks on human health (Heinrich & Lang, 2019). In this example, Resourses and Methods Couple plays an important role to represent any sustainability issues in the targeted material or product.

#### 3.4.4.7 Resilience

The resilience of the built asset industry against natural, financial, and social disasters/hazards has become increasingly important (Sertyesilisik, 2017). Recovery of the built assets in the post-disaster phase depends on reliable data that can be used to recouple historical information with new measures. This is due to the complex nature of reconstruction which involves many uncertainties and conflicts among stakeholders (S.-H. Wang et al., 2015). Moreover, real-time data about generated wastes as consequences of disaster should be recoupled in order to improve waste management and, ultimately, resilience of built assets in the future.

In the pre-disaster phase, defined codes, policies, and safety measures can be coupled with designs, methods, and resources using Information Couples. Model-based simulations can also be coupled with physical built assets to visualize potential risks on the built asset, environment, and human health.

#### 3.4.4.8 Compliance

Built asset industry involves with many activities and processes that should be traced and monitored to ensure the compliance with rules, requirements, constraints, and many other factors (A. Akanmu & Anumba, 2015). Compliance checking and monitoring are highly dependent on the availability of processed data, particularly when it comes to the actual status of assets and resources (milestones 5 to 8). Indeed, historical data about targeted resources and methods, asset deliverables, and initial purposes of building an asset play significant roles to support compliance checking of as-built physical and digital assets.

As mentioned earlier, Information Couples are capable to keep data inputs and outputs, and couple them with as-built assets. Such capability can provide stakeholders with numerous opportunities to save significant time and effort on compliance checking. From organizational point of view, many internal/external requirements to meet business objectives may be changed during the asset's lifecycle (Ramesh & Jarke, 2001). For these cases, an effective compliance checking requires updated requirements that are potentially coupled with the built assets. Depending on the compliance objectives, such data can be potentially offered by Information Couples, ensuring that no hidden information is missed over the course of compliance checking.

### 3.4.5 Coupling Impacts

In the broadest sense, the impacts of any coupling action can be categorized into (i) economic; (ii) environmental; (iii) social; and (iv) governance. Based on the mentioned coupling purposes and outcomes, a combination of such impacts can be observed at different scales. A hierarchy of Coupling Impacts is presented in Figure 3.8.

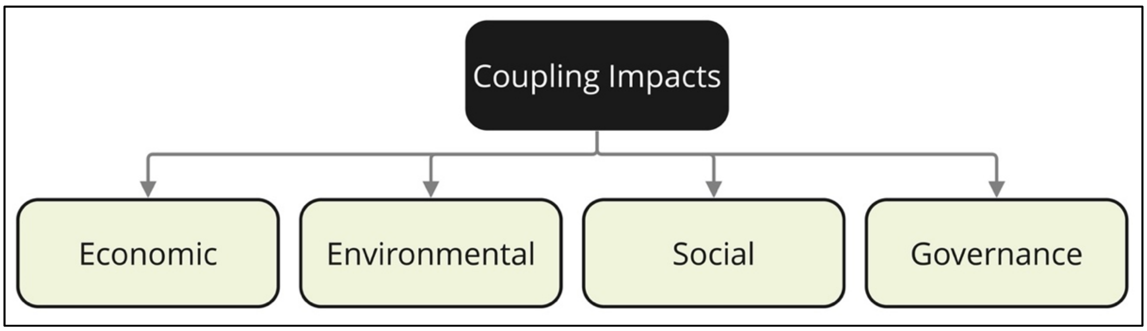


Figure 3.8 Coupling Impacts

#### 3.4.5.1 Economic

Several studies have recognised profitability of construction projects as a critical factor in overall economic growth (Jahan et al., 2022). According to Farnsworth et al. (2015), the profitability of the built assets depends on ability of stakeholders to build larger projects with shorter construction time and improved client satisfaction. Considering such variables, coupling of the planned costs and the actual costs (AC) is an effective way to increase the profitability of the built asset. This can be facilitated by optimising existing cost structure of assets and their potential values in the future.

Utilization of recovered built assets is another important factor in economic growth. Information Couples can dynamically capture and record financial values of as-targeted or as-built assets and resources, and then provide them for stakeholders to help them make better decisions about opportunities in secondary markets, value creation from waste, and value creation of reused assets (G.-Y. Kim et al., 2021).

From a commercial point of view, assessing and forecasting the total cost of asset ownership over its lifecycle is inevitably important for economic growth. Several Life Cycle Costing (LCC) methodologies have been proposed by scholars and practisers to estimate residual values (Heinrich & Lang, 2019). Using the proposed Information Couples, all design alternatives and their impacts on lowering the overall "cost of ownership" can be assessed and projected based on the first-cost investments and life-cycle values (Hubbard, 2009).

#### 3.4.5.2 Environmental

An increasing number of studies have emphasized the importance of lifecycle cost assessments (LCA) smart indicators for analysing the environmental impacts of the built assets and resources throughout their lifecycle phases (A. Singh et al., 2011; Khasreen et al., 2009). However, establishing an effective lifecycle environmental analysis requires a comprehensive insight from all circulated materials, systems, resources, and products. Furthermore, a detailed set of data indicating material usage, energy consumption, land use, generated waste, and emissions must to be available across the asset's lifecycle (Sikdar, 2003). Such data can be coupled with corresponding environmental certification or policy to avoid any uncertainty about the long-term impacts of built assets.

From an organizational standpoint, Information Couples can potentially improve the transparency in consumption of resources (Katenbayeva et al., 2016). Most often, stakeholders should handle a significant volume of data about energy bills, generated waste on the construction site, natural hazards, and etc. Continuous coupling of such data from physical and digital assets may help stakeholders to act more responsibly towards environment and its natural resources. In the O&M phase, negative impacts of a built asset on environment can be rapidly diagnosed and prevented by availability of coupled information on material (e.g. biological, chemical, and physical properties), and generated waste (Heinrich & Lang, 2019).

#### 3.4.5.3 Social

Social sustainability of the built assets should meet critical aspects such as human rights and wellbeing, working conditions, governance, and etc. (Eisfeldt, 2017). Unlike lifecycle environmental assessment, a limited number of studies have proposed methods to analyze social impacts of the built assets in the built asset industry (Çimen, 2021; Heinrich & Lang, 2019). One critical issue is lack of accessible and integrated data on the working condition of individuals in construction practices (Heinrich & Lang, 2019).

Built asset lifecycle information coupling may go beyond the physical and digital assets and can be used to store and integrate any circulated data (Barni et al., 2018), including lists of involved parties in the project, competency and dependencies of team members, average wages, weekly hours of work per employee, and etc. According to Labuschagne & Brent (2008), the impact of coupled information on social sustainability can be investigated through four main categories: (i) internal human resources (e.g. employment opportunities, labour sources, career development); (ii) external population (e.g. health, education, housing); (iii) macro social performance (e.g. economic welfare, trading opportunities); and (iv) stakeholder participation (e.g. stakeholder influence, information provisioning). Each category can be analysed using defined information couples from planning to operation and maintenance of the built assets. Incorporating social performance indicators can also facilitate this process by providing real-time social data for decision-makers.

#### 3.4.5.4 Organization and project governance

While governance carries different meanings, it generally provides a framework for ethical and logical decision makings based on transparency, accountability, and responsibility (Müller et al., 2014). Governance requires particular skills, knowledge, and capabilities to oversee any activity or process within an organization and make effective decisions based on the reported information (Too & Weaver, 2014).

Thus, information is one of the critical elements to support decision makings. Yet, having a reliable, secure and realistic information remains a concern for most of the governors, managers, and regulators (Liu & Xie, 2014). In the context of project governance, stakeholders aim to obtain information about the project's status in order to apply necessary interventions and to ensure that the rules and decisions are aligned with the project requirements, goals, and objectives (Lappi et al., 2018).

Lifecycle information coupling of built asset and resources can have significant impacts on making decisions to steer an organization or a project's future actions, as well as coordinating the teams involved. Asset coupling enables efficient reporting process by rapid assimilation of project data and coupling them to information requirements at an organizational level. While organizations may have different needs for information, physical and digital data generated from people or machines can be categorised, coupled, controlled, and ultimately reported to organizational actors involved in strategic decision makings.

While the majority of organizations protect their data as a result of commercial competitions or security reasons, asset coupling can change this culture by placing the value on the outcome of an insight derived from data, rather than placing value on the data itself (Reeves & Maple, 2019). Applying such an approach would also be valuable for governors or managers to obtain insight needed from a project and use them effectively for decision making. Changing this culture can address many barriers in open data sharing and accelerate data insight in organizational practices.

Moreover, continuous coupling of lifecycle information can improve transparency and promote trustworthiness for project governance. Information couples are able to offer stakeholders transparent and trustful information on coupled physical and digital built assets and resources. All activities and processes coupled from early stages of an asset's lifecycle to its end-of-life can be plotted in detail for logical and ethical decision makings.

### 3.4.6 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 (Figure 3.9).

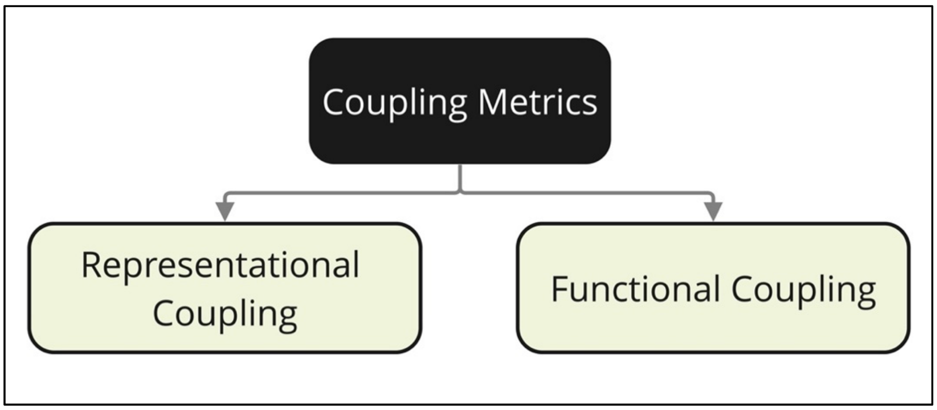


Figure 3.9 Coupling Metrics

#### 3.4.6.1 Functional Coupling

All Information Couples have intended functions. The functional coupling of the targeted/actual assets and resources can be examined to verify whether an information couple satisfies all the preliminary functional specifications. Functional metrics do not typically cover the technical specifications of every deliverable or method but emphasize on the overall functionality of Information Couples throughout an asset's lifecycle. Figure 3.10 represents potential metrics for assessing the functionality of Information Couples. Again, depending on different coupling purposes, the list can be extended or expanded by scholars and partitioners in the built asset industry.

In the following, each functional metric is described along with their measures:

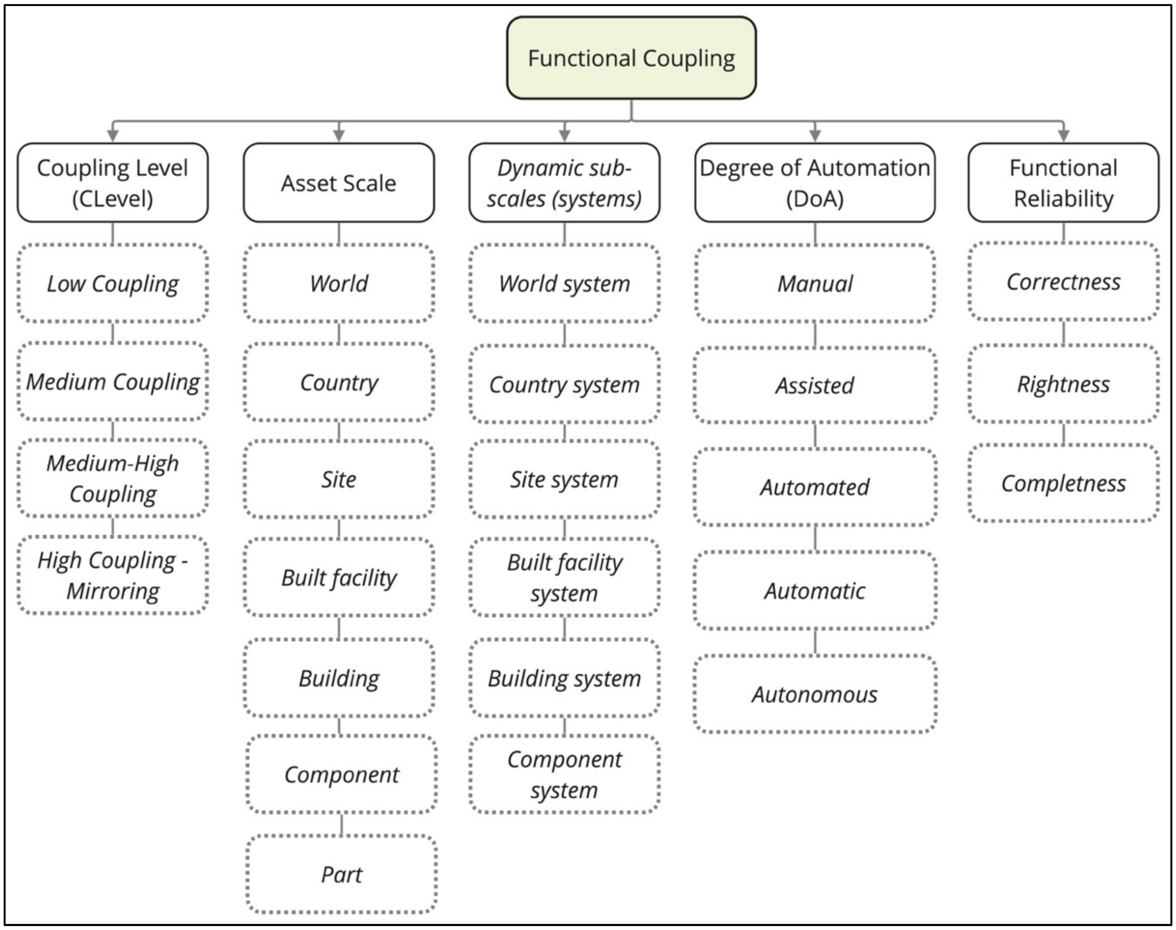


Figure 3.10 Functional coupling metrics

- Coupling level (CLevel): the extent of connectedness between the physical and digital built assets can be described by CLevel. An elevated CLevel represents the tight couplings and any changes in one asset may affect another in a real-time manner (Succar, 2019). CLevel includes four levels: (i) No Coupling; (ii) Low Coupling; (iii) Medium Coupling; (iv) Medium-High Coupling; and (v) High Coupling – Mirroring.
- Asset Scale: 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) (Succar, 2009).
- Dynamic sub-scales (System): refers to systems which are more/less granular than assets (Succar, 2009). Systems are capable to enhance information coupling of deliverables,

resources, and requirements of physical and digital built assets across multiple domains such as geographic information system (GIS), product lifecycle management (PLM), and BIM. Similar to asset scale, system sub-scales span from world system (e.g. GPS system) to component system (e.g. fan coil system).

- Degree of Automation (DoA): determines the extent of automation as physical and digital assets are coupled (Succar, 2019). DoA includes five degrees: (i) Manual; (ii) Assisted; (iii) Automated; (iv) Automatic; and (v) Autonomous.
- Functional reliability: determines to the ability of an information couple to perform the intended tasks correctly, completely, and rightfully with an acceptable and admissible results (Shubinski & Schäbe, 2013). "Correctness" of functional reliability refers to a failure free function. A reliable function should also satisfy the "Rightness" of a digital asset in comparison to its physical counterpart in terms of status, property, and position. "Completeness" means having all necessary parts, components, and condition to perform a reliable coupling action (L. Zhang et al., 2021).

#### 3.4.6.2 Representational Coupling

The representational coupling focuses on the nature of digital representation. The proposed metrics examines the levels/degrees to which a representation is transparent, faithful, accurate, complex, and failed. Figure 3.11 shows the hierarchy of representational coupling metrics. Each representational metric is described along with their measures as follows:

- Representation Fidelity (RT): refers to extent of faithfulness of a representation that is being used for coupling purposes. A digital model is faithful when it correctly mirrors different attributes of its coupled physical asset (L. Zhang et al., 2021). As representation Fidelity increases, users can trust representations more and use them for automatic decision making (Burton-Jones & Grange, 2013). It is often difficult to precisely determine the representation fidelity of a model. However, a faithful representation should be complete (having all detailed parts and components of a physical object), meaningful (having all useful semantics within a model), clear (clear representation of external structures and internal behaviors of the physical object), correct (error free geometrical/technical

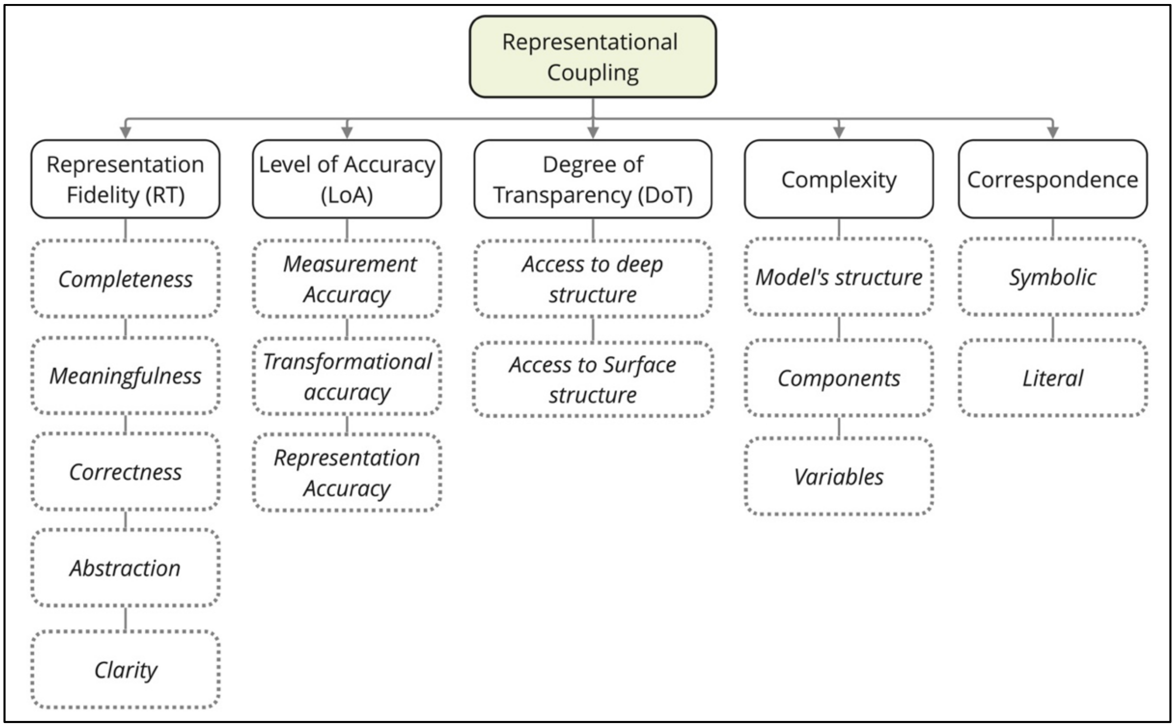


Figure 3.11 Representational coupling metrics

representation), and abstract (a model that covers different features of a physical object from different viewpoints).

- Level of Accuracy (LoA): specifies how accurately a digital model represents properties and structure of a physical asset. Level of accuracy (LoA) is a high-level metric which addresses measurement accuracy such as LoA10, LoA50, and etc. (Succar, 2019), transformational accuracy such as accuracy in transforming simulation-based algorithms to human-readable model (L. Zhang et al., 2021), and representation Accuracy such as USIBD Standard Deviation (USIBD, 2016).
- Degree of Transparency (DoT): 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). Increasing of representation transparency provides users the feeling of competence, trust, and control over built asset information coupling. This results in effective interaction between Information Couples and users with high level of productivity.

- Complexity: it is favorable to keep a digital model simple as much as possible. Unnecessary complexity of a model is caused by its high representational fidelity (L. Zhang et al., 2021). The model's structure along with its components and variables defines the complexity. Yet, it is difficult to examine complexity of a digital model through quantitative index. The complexity can be qualitatively measured by underlying the negative impacts of coupled information in assist's lifecycle (e.g. poor performance in reuse or maintenance phase). Therefore, simplicity of the digital model should be considered, especially when representing large and complex assets.
- Degree of correspondence: specifies how closely properties of a physical asset are mapped into its digital representations (Price, 2008). Symbolic correspondence is mapping the characteristics of a physical asset in a very abstract way. In the contrary, literal correspondence entails closely mapping a physical asset into digital representation without the use of metaphors or allegories.

### 3.4.7 Coupling Enablers

Coupling enablers are the key technologies needed to operationalize lifecycle Information Couples. The coupling enablers have been categorized into hardware, network, and software (Figure 3.12). Potential technologies for each category can be used to construct, evaluate, manage, and support Information Couples throughout lifecycle phases of assets and resources. These enablers are evolving rapidly of course.

Coupling enablers along with their capability sets support coupling actions. Here, the capability set specify the ability of enablers to satisfy a requirement or generate a deliverable or data (Underwood & Isikdag, 2010). To determine an enabler's level of capability, Succar (2009) defined three levels of BIM stages (from 1 to 3) through which the quality, maturity and performance of an enabler can be determined in practice.

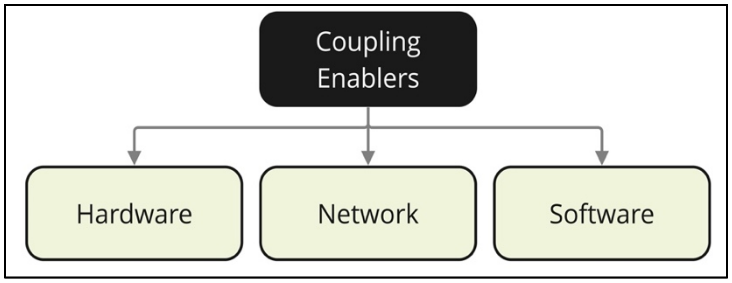


Figure 3.12 Coupling Enablers

#### 3.4.7.1 Hardware

The term “hardware” refers to physical things such as tools, machinery, equipment, digitizers, and etc. To ensure seamless information transformation and exchange, reliable hardware needs to be incorporated into the project, whether before or during construction and operation (Pang et al., 2021). In the context of built asset lifecycle information coupling, an enabled hardware must have enough capacity to handle a large volume of data in real-time manner and provide powerful and agile computing upon data acquisition. Such capabilities facilitate coupling of the physical with the digital in terms of simulation, mobility, and end-to-end business processes (Yaqoob et al., 2020).

As described in section 1.3.4, taking advantage of IoT devices is necessary to enable sharing of data between digital and physical assets through sensory devices (Lu et al., 2020). IoT devices should be able to remotely connect with the internet and also support interaction with other smart devices in the project (de Brito et al., 2018). Integration of IoT with AI-based solutions can also enable Information Couples to learn from processed data and suggest actions to control or avoid in different circumstances (El Saddik, 2018).

Haptic technology, also known as 3D touch, is another important enabler which enhance communication between the physical and digital built assets by integrating haptic properties. Haptic devices translate any changes in physical asset (e.g. displacement due to force, deformation under gravity, weight, etc.) to digital asset (e.g. 3D model) by acquiring and rendering contextual data. The hardware of haptic technology mainly includes computer as well as graspable, wearable, and touchable equipment (Y. Tang et al., 2020).

### 3.4.7.2 Network

Communication networks enables knowledge management by linking and maintaining information flow between the physical and digital environments (Trach & Bushuyev, 2020). To facilitate bi-directional information transformation and exchange between physical and digital assets, communication networks can be implemented particularly for remote activities (A. Akanmu & Anumba, 2015). Adopting suitable communication network depends on several factors such as geographic situation, data transfer rate, cost, range, etc. (X. Shen et al., 2008). Currently, wireless network protocols (e.g. Wi-Fi, WPAN, WLAN) are the most prominent and effective solutions in terms of coverage, cost, accessibility, stability, and robustness (Vossiek et al., 2003).

With the transition towards 5G networks and beyond, real-time information coupling occurs with a greater speed in transmission, a lower latency, more secure connections, and less power consumption. Information Couples can actively provide feedback loops with high speed and bandwidth via 5G networks, underlying the Coupling State under various conditions (El Saddik, 2018). 5G networks can highly accelerate information transformation and exchange between couples especially when combined with other advanced technologies such as AI, AR, and VR.

In order to actively store and learn from coupled information and their non-linear relationships, artificial neural networks (ANNs) and simulated neural networks (SNNs) can be implemented for a wide range of coupling purposes which require prediction and automation. ANNs use training data along with accurate learning algorithms. Unlike manual identification of data, ANNs recognizes acquired data (e.g. images, videos, codes, etc.) from physical assets with high speed and then learn from inputs based on mathematical functions (Stojanovic, Vladeta, 2021). Using the ANNs can significantly reduce human involvement in perceiving deep structure of data and learning from previous or similar information couplings.

#### 3.4.7.3 Software

Software refers to system, application, driver, middleware, and programming tools that support inter-operability and enable Information Couples implementations. Most often, software tools integrate with other specialized software tools (e.g. structural assessment, energy analysis, architectural modeling, etc.) to generate different kinds of model-based digital deliverables (Succar, 2009). Built asset lifecycle information coupling heavily relies on software tools that have capabilities to compute, process, model, and visualize transmitted information from physical space.

In the context of built asset industry, a wide range of commercial software tools have been offered to manage or operationalize different aspects of lifecycle information management. BIM-authoring tools are the most common solutions allowing users to design, model, develop and manage digital assets across lifecycle phases (Alonso et al., 2019). According to Aengenvoort & Krämer (2018), maintenance of Information Couples highly depends on the BIM deliverables during design and construction. Although BIM-authoring tools can be considered for the whole asset's lifecycle, their applications should leap from a static BIM to cloud-based paradigms (Boje et al., 2020). Currently, many software developers such as Autodesk and Bentley are offering their products as cloud-based solutions, allowing data to be bi-directionally transmitted between personal desktop computers and cloud environment via add-on or plug-in modules.

To decentralize data resources from local servers, various cloud-based solutions have been proposed to perform all the same functions within a CDE. As benefits of CDEs are becoming evident, the coupled lifecycle information can be accessed and managed by multiple users at the same time from different locations (Preidel et al., 2017). The incorporation of BIM models into CDEs can also assist stakeholders in developing or modifying coupled digital assets without having to deal with common interoperability issues in software tools (Mirarchi et al., 2020).

### 3.5 Coupling Action Instantiation Framework

The proposed Coupling action instantiation framework includes principles and mechanisms that enable application of lifecycle information coupling of physical and digital built assets and resources at different organizational scales. While the taxonomy described in the previous section specified *what* dimensions and characteristics should be considered for asset coupling, the coupling action instantiation framework focuses on *how* information couples can be

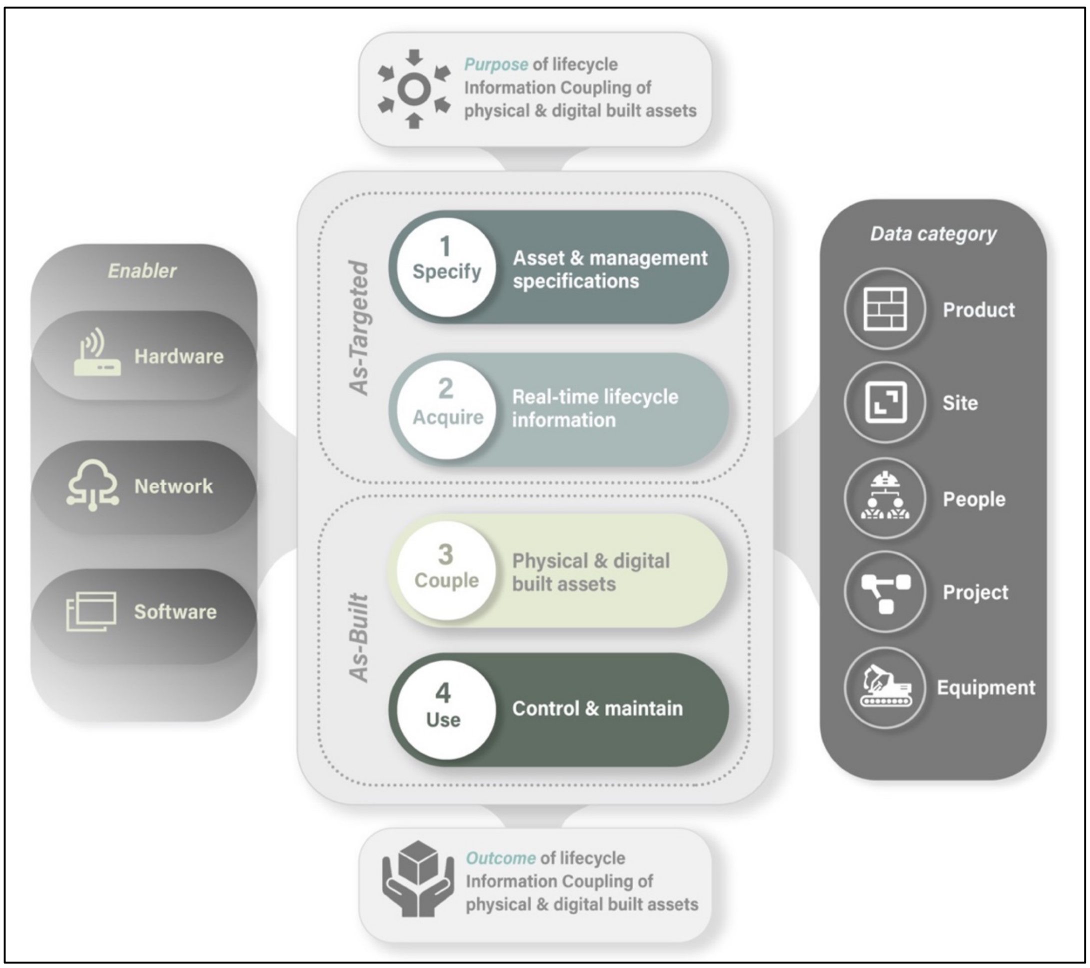


Figure 3.13 Coupling Action Instantiation Framework

generated and used. An instantiation framework should be capable of supporting a wide range of coupling purposes and leading coupled information toward expected coupling outcomes.

The coupling action instantiation framework is composed of conceptualized components that need to be understood, evaluated, and implemented in practice. In order to gain a clear and general picture of the coupling action instantiation framework, Figure 3.13 summarizes conceptual components that are framed to enable lifecycle information coupling of built assets and resources. As depicted in this figure, the coupling actions as the central component of the framework are divided into two information statuses: an "as-targeted" representing what information needs to be specified and acquired; and an "as-built" status representing what information is already coupled and ready to use (Succar & Poirier, 2020).

The reason behind such a division is that as-targeted information is usually specified and acquired to transmit information for the coupling action, while as-built information can be found in the coupled digital and physical built assets and resources. It should be noted that as-targeted and as-built information can be identified either in the physical form in the built environment, and digitalized within the information containers (models, documents, data). Thus, this division is defined according to sequence of coupling actions to highlight the status of information at each action.

In addition, the framework overlays defined dimensions and characteristics of the taxonomy, including coupling actions, coupling purposes, coupling outcomes, and coupling enablers. In addition, data needed to operationalize coupling actions are categorized at a high level along with their common characteristics and features. By being aware of data categories, the coupling actions can be applied and evaluated more comprehensively to meet their specific purposes. Further explanations of coupling action, data categories, and coupling mechanism are provided in the following sections.

### 3.5.1 Coupling Actions

Coupling actions are the methods and activities through which Lifecyle Information Couples are created and maintained. There are four coupling actions: Specify, Acquire, Couple, and Use (Figure 3.14). After identification of coupling purpose, a coupling action occurs through the mentioned principles. A brief description of each action is provided based on their sequence in the following sections.

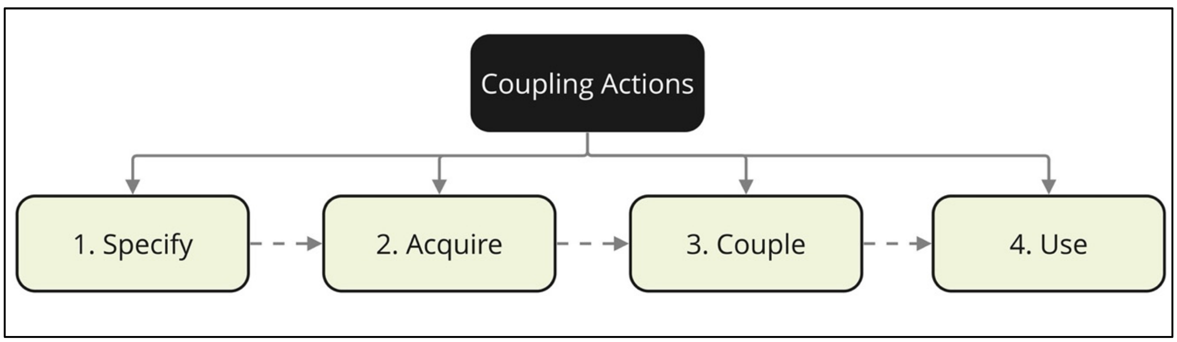


Figure 3.14 Coupling Actions

#### 3.5.1.1 Specify

After establishing the coupling purpose, the first step is to specify as-targeted data that are needed for built asset lifecycle information coupling. The term "as-targeted" here refers to both pre-existent data (e.g. digital documents of a physical asset that have already been created) and non-existent data (e.g. project secludes or design models that are needed to be created). In either case, all specifications related to as-targeted asset and project should be thoughtfully defined at this step by stakeholders (e.g. project owners, managers, regulators, etc.) in response to detailed requirements.

All specifications should be accessible and support various aspects of built assets lifecycle information coupling so that users can easily recall them at any time. In addition, a successful specification of as-targeted data relies on careful investigation of all heterogeneous databases across disciplines. For this, effective collaboration of stakeholders is required to structure all specifications in accordance with the coupling purpose.

#### 3.5.1.2 Acquire

Data acquisition is a vital part of the coupling action (Pang et al., 2021). Data can be manually and automatically acquired from existing physical or digital built assets (Haße et al., 2020). Stakeholders must be aware of how to convert acquired raw data into actionable information (Uhlemann et al., 2017). This involves data processing (e.g. cleaning, structuring, calibrating, clustering) (Østerlie & Monteiro, 2020), semantic translation (Dittmann et al., 2021), and storing data into a reliable physical or virtual database (Zheng et al., 2019). In addition, some scholars have emphasized edge analytic capabilities which perform additional analytical tasks on top of raw data to support better data processing and analyzing (Intizar Ali et al., 2021).

Ultimately, information models are crucial to utilize acquired data for coupling purposes. An information model digitizes all models, documents, data sets acquired from the physical space (ISO 19650-1, 3.3.8). Depending on the project deliverables, information models may be existing or need to be developed from scratch. In any case, parametric modeling methods may be needed to develop a global information model (Zheng et al., 2019), including all sub-models from different disciplines (e.g. architecture, mechanic, structure, etc.). According to Trebbi et al. (2020), the presence of enablers can maximise the benefits of information models by decentralizing information from local platforms and keeping them up-to-dated for effective collaboration across the asset's lifecycle.

#### 3.5.1.3 Couple

The construction of lifecycle Information Couples, as introduced in section 3.4.1, is the focus of this step. The preliminary data acquisition in previous step continued with formation of the global information model. Such information model can be implied as a digital asset which is ready to be coupled with the physical asset. Depending on the type of Information Couple, a global information model may contain specific data pertaining to purposes, targeted/expected deliverables, and needed resources and methods of an asset.

To couple information between the digital asset and the physical asset, every component of a physical asset should find a corresponding instantiation within the digital asset (F. Jiang et al., 2021). Here, an instantiation means digital counterpart of a specific physical asset, deliverable, or resource and method (Boschert & Rosen, 2016). Depending on coupling purpose, these digital instantiations can be represented as an "instance" of a given data, either an abstract instance or detailed instance. In either case, digital instantiations should be informative and faithful particularly in the situations where users looking for computational rendition of reality (Ekbia, 2008).

Next, changes in the physical and digital built asset should be communicated through bi-directional interactions that makes the special demands on synchronization (Strassburger et al., 2005). In the physical space, an asset can be facilitated with actuators to receive signals from virtual-world and perform required actions (Boje et al., 2020). In fact, immediate actuation of a physical asset is one of the important abilities of the asset coupling which can be augmented by virtual sensors within the digital model (IES, 2020). To knowledge people in the real-world about applied changes on the digital built asset, the use of information viewers such as virtual reality (VR) headsets, desktops, and handhelds is necessary to display data (e.g. by image mapping between simulation and virtual reality environment) and allow users to interact with data through a flexible UI. Such interaction can be advanced further by using tangible user interfaces (TUIs), which aim to take advantage of the haptic skills and provide users direct control and manipulation of coupled information in real environment (Ishii, 2008).

Continues information coupling between components of the physical asset and their digital instantiations within the digital asset results in formation of the Information Couple which consists of both physical and digital data. An Information Couple is not an asset or a resource itself. Whereas it is an abstract concept that refers to interpretation of information which has been coupled from physical and digital built assets and resources. In the pursuit of knowledge, Information Couples can be encoded into various forms of representations, interpretations, and transmissions. Although Information Couples are expected to keep physical and digital assets and resources highly coupled, the CLevel may varies depending on the coupling purposes or expected outcomes. Nevertheless, an Information Couple aims to maintain physical and digital information that are accurately matched and convey them for various industrial practices.

The coupled information between the physical and digital built assets should be continuously monitored and validated to mitigate any reduction in CLevel (L. Zhang et al., 2021). The technological configuration of coupling enablers should be flexible and adaptable based on user needs. For example, users should be able to easily switch from Bi-directional to Uni-directional information coupling. However, remaining on Uni-directional state does not allow feedback from one side of the coupled information (Dorozhkin et al., 2012). Further automated validation and verification technologies can be implemented to manage the changes and correctness of Information Couples (L. Zhang et al., 2021).

#### 3.5.1.4 Use

After formation of Information Couples, the effective use of coupled information is the last step in the coupling action. Based on the Coupling Purpose, there are several ways to use data accumulated within Information Couples.

One common approach is to extract data for a particular purpose. Pinheiro & Goguen (1996) proposed three main mechanisms for extracting data from Information Couples: (i) selective; (ii) interactive; and (iii) non-guided. In the selective extraction, the users may select and consider a certain type of data or relationships, and then extract data without spending time on other alternatives. Interactive extraction allows users to browse over a large volume of data within an Information Couple and try different paths to help in navigation process. Non-guided extraction includes going from one datum to another and controlling data as desired. There is no particular path to be followed in non-guided extraction and it is suitable when a user knows what and how to extract.

Another approach is to visualize coupled information through advanced data visualization techniques (Boje et al., 2020). As such, coupled information can be displayed using various solutions such as model-based simulations on CDE or local platforms (e.g. 3D model of the physical asset in BIM environment) (Stojanovic, Vladeta, 2021), augmented reality (AR) technology (e.g. smartphones) (Demestichas & Daskalakis, 2020), VR technology (e.g. head-mounted devices) (Rasheed et al., 2020), graphical charts (e.g. dashboard, histogram) (A. A. Akanmu et al., 2021), and etc. All exemplified solutions can potentially utilize coupled information for better decision-making and understanding the value generated for lifecycle information management.

In general, the list of approaches to use coupled information can be extended in accordance with Coupling Purposes. While digital information technologies are rapidly evolving, more coupling uses would emerge to address current and future barriers in the built asset industry.

### 3.5.2 Data categories

Lifecyle information coupling of built assets and resources depends on data that convey information for coupling actions. In this research, data refers to digital computable symbols – typically numbers and letters – that need to be digested before and after coupling actions. As different types of data could be generated and shared by various disciplines across lifecycle stages, recognizing and classifying such data is a big obstacle for current practices (Campos et al., 2020).

To avoid confusion regarding what type of data is needed, which data pertain to which activity or method, and who is responsible for what, data needed for coupling actions was divided into five high-level categories: (i) product; (ii) site; (iii) people; (iv) project; and (v) equipment. Table 3.1 summarises data category definitions.

Table 3.1 Data categories

| Data category | Definitions | Ref |
|---|---|---|
| Product | Data pertaining to a product (e.g. object, system, or service) that has an actual value and can be offered to meet a specific consumer need. A product can be physical (a tangible item) or digital (an intangible item) that consist of multiple data pertaining to its properties, parameters, components, parts, and etc. Examples of product data are design drawings of a door, commissioning reports of a door, assembly manuals, and etc. | (Bhattacharya et al., 1998), (Kotler, 2006), (Ríos et al., 2015) |
| Site | Data related to an earmarked parcel of land upon which a project and its related infrastructures can be located, constructed, and developed. A project site includes multiple data pertaining to site layout, geographic characteristics, ownerships, rights-of-way, principal changes, land used, and etc. | (Ibbs, 1984), (RazaviAlavi & AbouRizk, 2017), (J. P. Zhang et al., 2002), (Zolfagharian & Irizarry, 2014) |
| People | Data pertaining to a "person, organization or organizational unit involved in a construction process". People in a project may affect, or be affected by a decision, activity, or outcome across lifecycle stages. Examples of such data are list of roles and responsibilities, competencies, dependencies among people, working hours, working benefits, working outputs, and etc. | (ISO19650-1, 3.2.1), (Project Management Institute, 2013), (VanDemark et al., 2019), (Cherns & Bryant, 1984) |
| Project | Data pertaining to a project that includes temporary endeavor undertaken to deliver a unique product or service. Data in a project enable stakeholders to | Project Management Institute, 2013), |

| Data category | Definitions | Ref |
|---|---|---|
| | manage, execute, evaluate, and ultimately make effective decisions on project delivery. Project data can be collated into documents and models derived from various disciplines (e.g. MEP, architecture, structure, etc.). Data in a project should be conformed with pre-set requirements and the constraints of time, cost, and resources. For example, data derived from work packages, project execution plan, project deliverables, project information model, and etc. | (Succar, 2009), (Abdul-Rahman et al., 2011), (Schwalbe, 2015), (Henrie & Sousa-Poza, 2005) |
| Equipment | Data pertaining to "a set of tools or objects used to achieve a particular objective" within a project. here, a tool may be general such as hand tool, power tool, and machines, or specialist tools such as software tools, measuring devices, and etc. Data in this category specifies various aspects of equipment used in a project such as their, values/prices, capabilities, outputs, operation status, technical/functional properties, emissions, and etc. | (Nahmias & Olsen, 2015), (Prasad Nepal & Park, 2004), (Gransberg et al., 2006) |

Such categories overlay data pertaining to physical and digital assets, as well as management of resources and methods. Depending on coupling purposes, data categories may consist of more specific and detailed data related to processes (e.g. resources, products and services, leadership and management, activities), policies (e.g. protocols, mandates, guides), and enablers (e.g. hardware, software, and network). Therefore, existing or expected data should be first grouped into one of the defined data categories and then be deployed for coupling actions (specification, acquisition, coupling, and using).

From a technical standpoint, categorized data could be either volatile and non-volatile (Uhlemann et al., 2017). All dynamic activities and processes that need to be acquired in a timely manner are referred to as volatile data (e.g. movements of equipment, temperature variance). Using IoT devices can minimise human involvement to automatically acquire volatile data (Rajput & Singh, 2019). Non-volatile data are static by nature and can be acquired through measurements or interviews (e.g. list of ordered equipment, bills of energy).

### 3.5.3 Coupling mechanism

Lifecycle information coupling of built assets and resources is based on the multiple interactions between coupling actions and other components of the framework. To understand better these interactions, a high-level coupling mechanism was proposed to identify the processes and activities needed to link real operational data to coupling actions. Figure 3.15 summarizes how coupling mechanism operate using a matrix of categorized data and coupling actions. This figure also shows other components of the framework, including embedded operational data, coupling enablers with their capability sets, and coupling actions which are all linked together to operationalize data for addressing coupling purposes

The matrix of categorized data and coupling actions was set to align defined actions with targeted or actual data embedded in information containers. The emphasis here is on data that has the potential to be coupled to address a purpose across an asset's lifecycle. Such data could exist in information containers, or it has to be acquired in next steps. Here, an information container refers to "named persistent set of Information retrievable from within a file, system or application storage hierarchy" ISO 19650-1 (3.3.12). A file refers to documents (e.g. e-mails, a PDF document) and models (e.g. geometrical /graphical models) or combination of both that can be physical and digital.

Not all embedded data in information containers would be pertinent to the coupling actions. Thus, potential data uses should be recognized and categorised based on the project goals and objectives. Most often, a large volume of data is embedded within information containers by

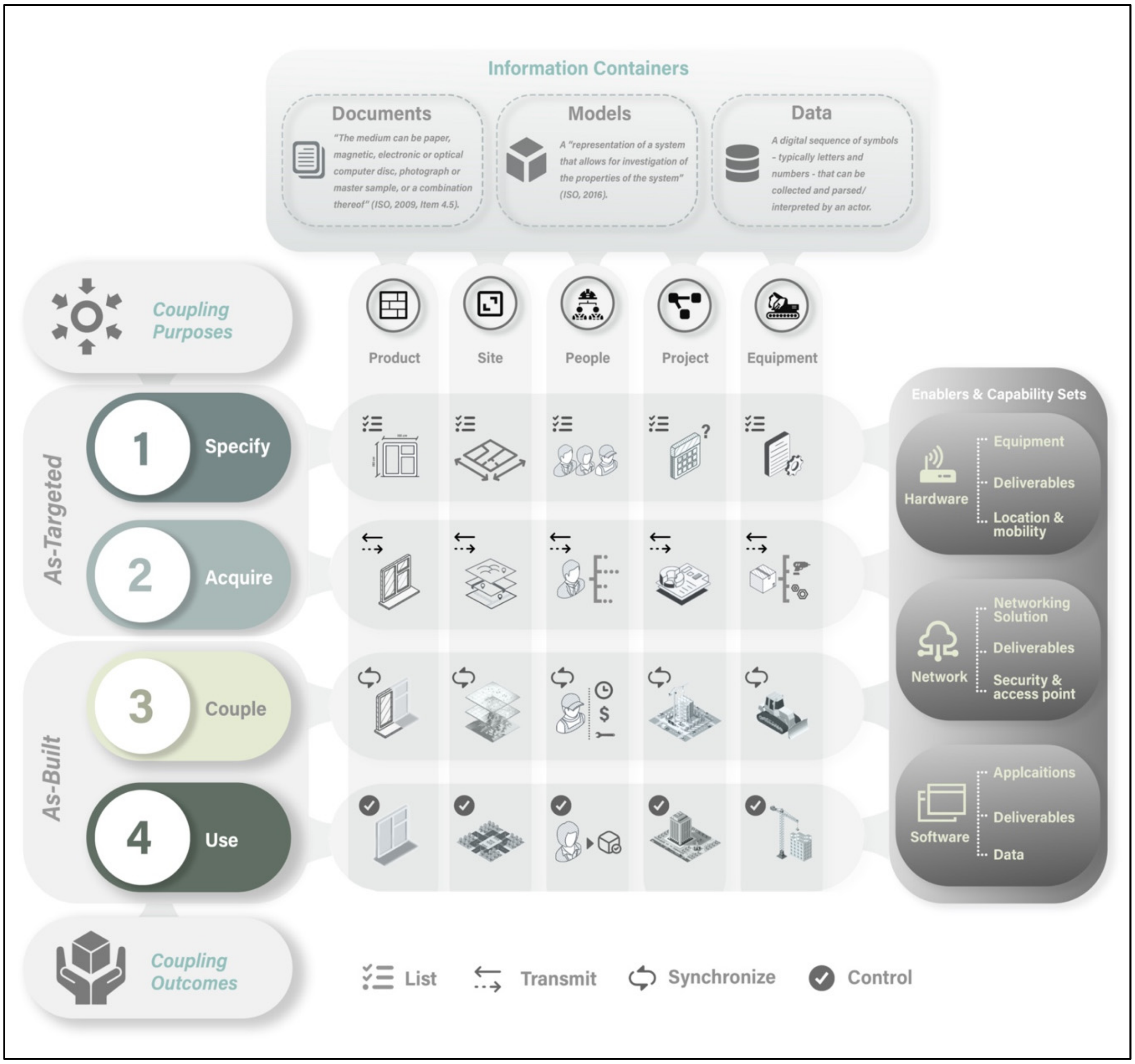


Figure 3.15 Coupling Mechanism

various disciplines which must be properly interpreted and coordinated before being used for coupling actions. In such a situation, integrated data environments are promising solutions that allow multiple stakeholders to manage data categories and structures in a shared digital ecosystem (Succar & Poirier, 2020). An integrated data environment can be further facilitated by coupling enablers such as software solutions to structure granular information through middleware and plugins. To incorporate categorised and structured data into coupling actions, a number of sub-coupling actions need to be carried out. Sub-coupling actions refer to subactivities or sub-processes to transform asset information into action. In the context of coupling actions, four sub-coupling actions were identified as follows:

1. *Listing* specifications of the targeted assets or resources.
2. *Transmitting* data from targeted assets and resources.
3. *Synchronising* as-targeted and as-built data.
4. *Controlling* coupled data before use.

Depending on type of lifecycle information couple, sub-coupling actions may require specific methods, strategies, drivers, or enablers. For each sub-coupling action mentioned above, an extensive number of techniques and methods can be found in the literature. According to Zhang et al. (2021), *listing* the specifications involves with extracting, describing, and verifying knowledge content clusters of assets and resources. Knowledge content clusters are guides, protocols, and mandates which can be subdivided into eighteen knowledge content labels such as reports, contracts, manuals, plans, requirement, and etc. (Succar, 2009). *Transmitting* data from the physical asset (e.g. building component, systems) and digital assets (e.g. models, documents) heavily relies on coupling enablers to convey meaningful information for the acquisition action (El Saddik, 2018; Jiang et al., 2021; Tao et al., 2019).

In as-built status, *synchronizing* data between physical and digital built assets and resources is critical to form and maintain Information Couples. Data synchronisation can be done continuously in a coupled state, updating physical and digital built assets with real-time data. However, there might be no synchronization at all in a coupled state (Haße et al., 2020). Lastly, *controlling* data entails commissioning or controlling of coupled built assets which are ready to be used (Aengenvoort & Krämer, 2018). Control mainly focuses on coupled outputs delivered by humans and machines to ensure the quality and performance of built assets and resources (Yaqoob et al., 2020).

As an example for coupling mechanism, if the coupling purpose of a project is seismic monitoring of a bridge's structure, stakeholders may determine that specific data is needed such as properties of trusses (product), topography of the surroundings (site), involved teams in the monitoring process (people), work breakdown structures (project), and available monitoring devices (equipment). In this example, such data would be listed, transmitted, synchronized, or controlled for their specific coupling actions (section 3.5.1) to achieve the desired coupling outcome (e.g. prediction of seismic risks within a certain period of time). While Figure 3.15 illustrates arrangements of data into rows and columns of the matrix, these data are not definitive and can be any meaningful data for a particular coupling purpose.

Overall, coupling mechanism heavily relies on linking right data to its corresponding coupling actions through the use of coupling sub-actions and enablers. While a large volume of operational data may be embedded into multiple information containers, the main approach is to categorize and structure them as much as possible before any coupling action. Using of appropriate coupling enablers can significantly reduce the amount of time to categorize, link, and couple lifecycle information. Indeed, coupling enablers are essentials to support coupling sub-actions and to form information couples across asset's lifecycle.

## 3.6 Chapter Summery

This chapter introduced a taxonomy of Built Asset Lifecycle Information Coupling, as well as its instantiation framework to identify the key dimensions and characteristic guiding this trend towards the coupling of physical and digital assets and resources. The proposed taxonomy can serve as an artifact to investigate the concept of asset and information coupling in the built asset industry. The key dimensions and characteristics of the taxonomy are based on the coded data and analysis from reviewed literatures in the domain. The dimensions support different aspects of asset and information coupling including their types, states, purposes, outcomes, impacts, actions, metrics, and enablers. Each dimension was introduced along with its potential characteristics. Such characteristics disclose central, distinguishing principles, and properties of lifecycle information coupling. They can potentially enhance industry stakeholders in making effective decisions during the lifecycle information coupling of built assets and resources.

In addition, an instantiation framework was developed to investigate how dimensions of the taxonomy can be implemented in real practices. The coupling action instantiation framework includes several key components such as coupling actions, data categories, coupling purposes, coupling outcomes, and coupling enablers. Such framework can be evaluated and used in multi-disciplinary case studies through a coupling mechanism that integrates embedded operational data within information containers to defined coupling actions. Using the matrix of coupling actions and data categories allows stakeholders to better identify potential data for coupling purposes, and then use them during coupling action to achieve the desired coupling outcome. Moreover, this framework can be used for ex post evaluation to set a solid basis for research artifact and to examine reliability, validity, applicability, and accuracy of the research constructs.

Overall, the proposed taxonomy and its instantiation framework contribute to the effort aimed at structuring the knowledge domain of lifecycle information management through the coupling of physical and digital assets and resources in the built asset industry. As a nascent field of study, the proposed constructs in this chapter should be further developed, evaluated, and implemented to fully unlock their potentials.

# CHAPTER 4

# RESEARCH RESULTS

This chapter reports the main findings of the research project obtained through the evaluations and data analysis. As described in section 2.7, two case studies were selected to evaluate the research constructs proposed in Chapter 3. While case studies were selected from various contexts, the coupling action instantiation framework covered most of the functional and representational aspects of the asset coupling. The results of each case studies are presented in the following sections.

## 4.1 Findings from case study 01: A steel truss cantilever bridge

### 4.1.1 Coupling purpose of the bridge

The context of this case study was structural health monitoring of the bridge through thermal monitoring of the assets over a two-year period. Based on the defined coupling purposes in the taxonomy, the main purpose of this project was considered “Monitoring”. This underlines required actions and processes to couple built assets and resources for thermal monitoring of structural members such as trusses, bearings, connections, beams, and etc.

### 4.1.2 Coupling outcomes of the bridge

The primary coupling outcome was obtaining “insight” about various parts of monitored data from the bridge and their digital counterparts in the models, reports, or drawings. Another coupling outcomes was “resilience” against financial risks, natural disaster, and social crises. In fact, lifecycle information coupling of the bridge and its listed/modelled digital information (e.g. seismic characteristics of the site, cost schedules, safety measures for workers) showed that having such coupled data on hand can improve the bridge's resilience until 2026.

### 4.1.3 Information containers and data categories of the bridge

Review of the information containers of the case study showed that the Revit model of the bridge was the only digital parametric source. While this model was still in progress at the time of ex post evaluation, it basically provided information about technical data of structural members, positions of sensors, and an abstract representation of the project site with its features. Regarding the documents, a variety of reports and references were available in the SharePoint. Table 4.1 shows category of reviewed documents.

Table 4.1 Number of reviewed document and their relevant data categories

| **Document category** | **Number of reviewed documents** |
| --- | --- |
| Drawing | 19 |
| Design report | 4 |
| Environmental report | 4 |
| Assessment report | 4 |
| Inspection report | 7 |
| Monitoring report | 6 |
| Others (e.g. cost, waste) | 3 |

As shown in Table 4.1, available documents were mostly reports, specifying the results of monitoring, assessment, and inspection activities. The majority of drawings provided necessary data about as-built structural members (e.g. constructed beams and trusses) and as-targeted structural members (e.g. expected replacements to resist thermal deformations). Other drawings were used mainly to extract data about project's site such as existing mobility connections, environmental damages, and etc. The reports of the project were mainly focused on the bridge as a large scale physical asset and its relevant component systems (e.g. frame system, foundations). All specifications regarding design of the components, their technical and functional properties were assigned to the product category of the framework. A limited number of documents were found about the project itself and people involved in the thermal monitoring process. These data were widely extracted from reported monitoring activities and other documents about cost analysis, risk registries, and etc.

### 4.1.4 Evaluation of coupling action instantiation framework: case study 01

After extraction of meaningful data from information containers, the coupling action instantiation framework was implemented to evaluate how these data can be used for coupling actions. Figure 4.1 illustrates the framework including linked data related to structural health monitoring. Based on the review of documents and model, the potential operational data for coupling actions were identified. Table 4.2 summarizes identified data categories and their sources form this case study.

Table 4.2 Identified data for coupling actions

| Coupling Action | Data Category | Identified Data | Source |
|---|---|---|---|
| Specify | Product | Rehabilitation specifications for the structural members of the bridge (e.g. trusses, frames, beams, foundations, etc.). | • Assessment report<br>• Monitoring report<br>• Design report |
| | Site | Geographical characteristics of the land (e.g. river, subsurface condition, external properties, directional orientation, traffic flow, etc.). | • Drawings<br>• Environmental report |
| | People | List of involved contractors, teams, and organizations for structural rehabilitations. | • Organizational chart |
| | Project | Thermal monitoring goals, objectives, supporting infrastructures, and expected deliverables, project requirements. | • Other reports<br>• Monitoring report<br>• Inspection report |
| | Equipment | List of required production and installation equipment based on their capability set. | • Drawings<br>• Environmental report<br>• Monitoring report |

| Coupling Action | Data Category | Identified Data | Source |
|---|---|---|---|
| Acquire | Product | Original and updated design drawings (e.g. plans, sections, elevations, 3D views, etc.) of the main structure associated with technical and functional attributes. | • Drawings<br>• Revit Model<br>• Design report<br>• Inspected report |
| Acquire | Site | Established measures and rules concerned with the engineering behaviour of the site affecting seismic performance of the bridge such as site coefficient, dynamic earth pressures on the walls, slope stability of the site, liquefaction potential of subsurface area, and etc. | • Drawings<br>• Environmental report<br>• Inspection report |
| | People | The roles, interdependencies, and competency of involved contractors and organizations for rehabilitation activities. | • Other reports<br>• Monitoring report<br>• Inspection report |
| | Project | Cost schedules and analysis of different monitoring stages, an abstract list of tasks for each team in a timely fashion. | • Other reports |
| | Equipment | As-targeted features of on-site and off-site equipment and their expected capability to support thermal monitoring, data analysis, and simulation. | • Monitoring report<br>• Inspection report<br>• Environmental report |
| Couple | Product | Functional and technical properties of real structural members with their digital counterpart in 2D/3D models in virtual space. | • Drawings<br>• Revit Model<br>• Inspection report |
| | Site | Principal changes in actual project site and identified/predicted changes in protocols, mandates, and guides such as location of temporary components (cranes, decks, scaffolds, etc.), logistics, and etc. (In progress) | • Other reports<br>• Environmental report<br>• Inspection report |
| | People | Actual activities by workers in the workplace with what has have been planned or scheduled in the specifications such as active monitoring or inspection hours (in progress). | • Inspection report<br>• Monitoring report |
| | Project | Status of planned tasks (humans and machines) in the virtual space and their progress in the actual workplace. | • Assessment report<br>• Monitoring report |

| Coupling Action | Data Category | Identified Data | Source |
|---|---|---|---|
| | Equipment | Status of in-used or un-used equipment (e.g. location, operation hours) in the actual workplace and the defined requirements or specifications in virtual space. | • Inspection report<br>• Monitoring report |
| Use | Product | Monitored and inspected structural members specifying their performance and quality against thermal changes. | • Inspection report<br>• Design report<br>• Drawings |
| | Site | A set of mitigation measures and rules to control seismic and flood risks on the site. | • Inspection report<br>• Drawings<br>• Environmental report |
| Use | People | Delivered works and completed tasks by teams along with task name, method of delivery, date, location, and etc. | • Assessment report<br>• Monitoring report<br>• Inspection report |
| | Project | All of the submitted physical and digital deliverables and their outputs within the scope of structural health monitoring. | • Inspection report |
| | Equipment | The actual output of equipment (e.g. sensors, gauges) and their consumed energy and resources, as well as generated wastes and carbon footprints at the end of the project (in progress). | • Monitoring report<br>• Inspection report |

While most of the extracted data were aligned with proposed data categories and coupling actions, their richness (extent of data/information embedded within a container) varied. This was mainly due to lack of available/accessible data in information containers, or the project was under progress at the time of evaluation. Figure 4.1 illustrates the instantiation framework including linked data and their different richness. High data richness is highlighted with green, specifying full availability of data from existing documents and models. Medium data richness is highlighted with yellow, specifying partial availability of data both in documents and models. Low data richness is highlighted with red, specifying poor availability of data at the time of evaluation.

In addition, Figure 4.1 represents specific coupling enablers and information containers of this case study. To enable coupling actions, three main enablers were found, including thermal monitoring and recording devices (hardware), predefined network systems to connect and match sensor data (network), and an integrated data environment fed by Autodesk Revit. The capability set of identified enablers was not available or accessible. The only accessible enabler was Revit software which was commonly used for object-based modelling (BIM Stage 1).

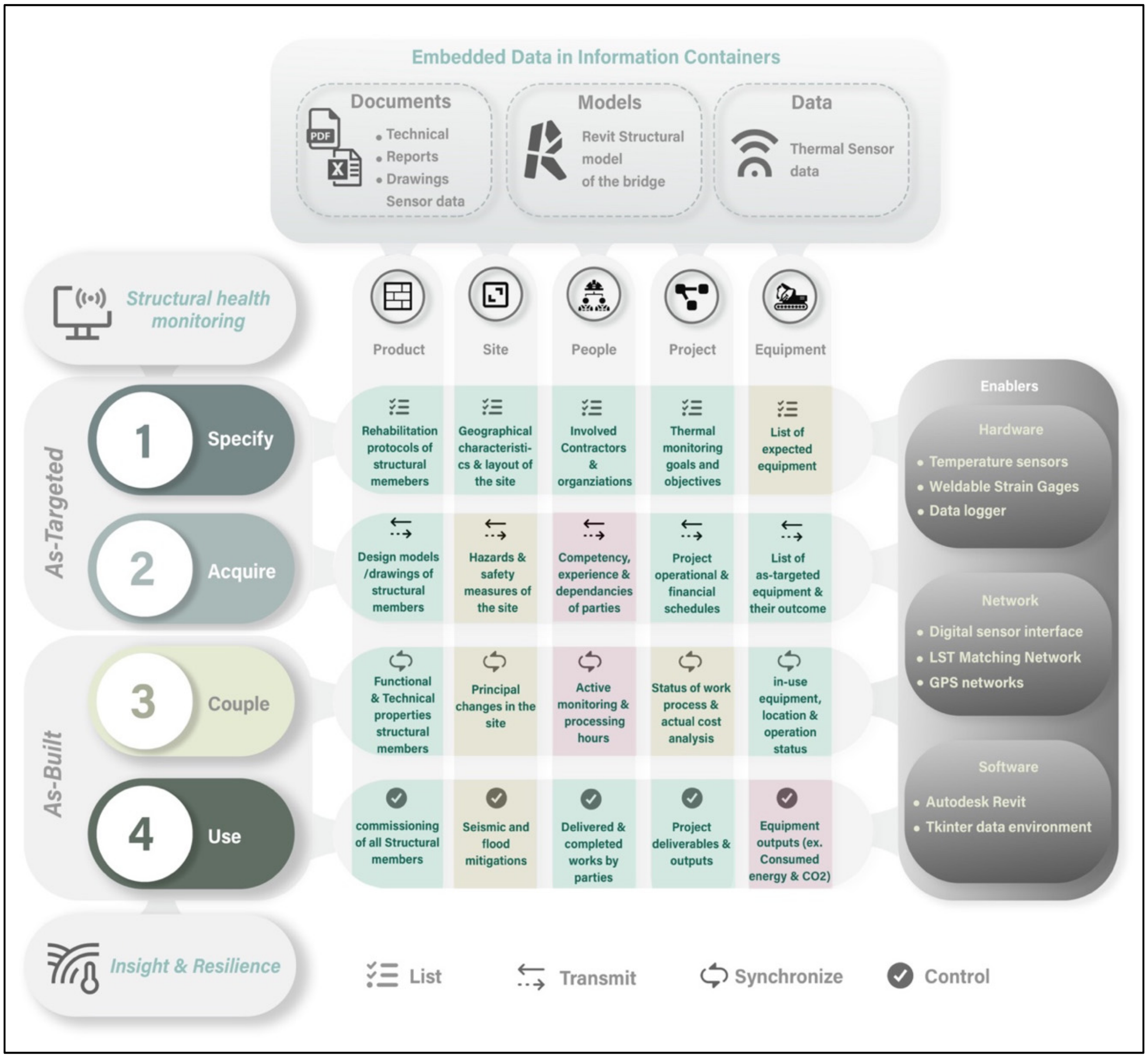


Figure 4.1 Implementation of the coupling action instantiation framework in case study 01

Regarding the CLevel of this case study, a great extent of data was already synchronized and inspected at the time of evaluation. Such data was mostly associated with Digital Couples (e.g. coupling of targeted design drawings of structural members with actual digital model of structures), and Resources and methods Couples (e.g. coupling of targeted monitoring methods with actual executed methods on project site). Therefore, the CLevel of this case study can be interpreted as medium-high coupling. While data related to thermal behaviour of the bridge was commonly transferred in a unidirectional manner, this project had the potential to achieve high coupling – mirroring if the existing digital model and documents were fully connected with all monitoring activities at the physical space.

## 4.2 Findings from case study 02: the commercial office high rise building

Based on the project context, it was found that the desired DT of the building can be regarded as a multi-purpose digital asset that reflects the operation and management practices of the physical building across its lifecycle stages. Multiple discussions with researcher participants were held to evaluate applicability of the proposed coupling dimensions of the taxonomy.

### 4.2.1 Coupling purposes and outcomes of a DT

According to strategic objectives of the company, one of the main purposes to develop a DT was delivering thoughtful and intentional spaces to improve the sustainability of building spaces as well as human health and wellbeing. Achieving these objectives required sustainable use of natural resources (e.g. energy, water), waste elimination, and minimizing carbon footprint across the building's lifecycle stages. The company has already conducted a decarbonization plan to achieve net zero carbon by 2040. This included new digital strategies for monitoring, continues energy performance analysis, fresh air management, controls optimization, and etc.

Considering the dimensions of the proposed taxonomy, coupling purpose of a DT in this case study can be classified as a combination of *analysis*, *automation*, and *monitoring* purposes.

The potential coupling outcomes of a DT implementation can be characterised into several values including: providing *insight* from building operation and management practices, providing high *quality* work environments for users, ensuring building *sustainability* and *resilience* against climate change, improving building *performance* in consumption of natural resources and elimination of carbon footprints and waste. All these values have direct coupling impacts on environment, economy, social, and governance.

Further evaluation of coupling purposes and outcomes was performed through a set of preliminary DT use cases covering various aspects of operation, services, and management practices of the building. While each use case was associated with coupling purposes, the partner organization provided feedbacks on the values of *sustainability* (e.g. environment, energy management, waste disposal, fresh air) and *resilience* (e.g. occupant comfort and adaptation in building ecosystem, less damage on human wellbeing and experience) as the key outcomes of DT implementation for the building. Therefore, it was found that potential Asset Couples should derive these values by keeping the physical and digital built assets at relatively high CLevel and DoA.

### 4.2.2 Evaluation of coupling action instantiation framework: case study 02

This case study was found as one of the important examples of planning for Asset Couples. While the building was in O&M phase, implementation of the coupling action instantiation framework was found as an avenue to couple the existing high rise building (physical and real) with its potential digital counterpart (digital and real).

To develop a DT of the building, a large volume of data such as guides, mandates, and protocols needed to be specified and acquired by developers. Such processes can be related to *targeted* state of the framework in which data specifications and data acquisitions were established to list and transmit meaningful data from actual situation of the building. For example, a wide range of provincial guides (e.g. provincial guidelines to promote sustainability of work environments), company mandates (e.g. renewable energy programme, decarbonization plan), and national/international protocols (e.g. wellness standards, leadership and energy measures) were embodied in information containers which needed to be listed and transmitted for as-targeted coupling actions.

Regarding as-built coupling actions, the result of the evaluation was only discussed with partner organization around future opportunities to couple and use the desired Asset Couple (DT). This was mainly due to lack of implementation strategies and facilitation of the building with necessary coupling enablers (e.g. IoT sensors, CDE) to execute the planned DT in real practice. In fact, this case study was still in early stages and a limited amount of actual data was available at the time of this evaluation. As a result, the coupling action instantiation framework was evaluated using only available data from available databases, on-site visits, and a review of similar practises. Identification of potential data for as-targeted actions was mostly based on company's goals and strategies to digitalize its operation and management practices. While the CLevel of this case study was expected to be medium to high, a large volume of data was found meaningful to be listed, transmitted, synchronised and controlled in coupling actions.

Figure 4.2 shows the implementation of the coupling action instantiation framework in this case study. Similar to case study of the bridge, the green cells represent the high data richness, the yellow cells are medium data richness, and the red cells are low data richness. In terms of information containers, only documents (PDF documents, Excel spreadsheets, PPT presentations) were identified as the main sources to provide necessary data for coupling actions. Aside from project execution plans/models, other targeted data pertaining to specification action and acquisition action could be found from the existing documentations. However, the majority of as-built data identified for coupling action and using action were found with medium and low data richness. This was mainly due to lack data about the actual situation of built asset in relation to desired DT systems. Nevertheless, the potential data for as-built actions were identified based on the project strategic objectives and site visits during the evaluation process.

Regarding the coupling enablers, the existing hardware and network solutions were identified during site visits. This includes various types of IoT devices (sensors, security systems, actuators, etc.) which were interconnected with Wi-Fi and WLAN services. The list of planned equipment for future state of the DT was also found in company mandates. However, it was not clear what were the main software solutions could be potentially used for implementation of a DT. Work is currently underway to develop and validate the framework on this project.

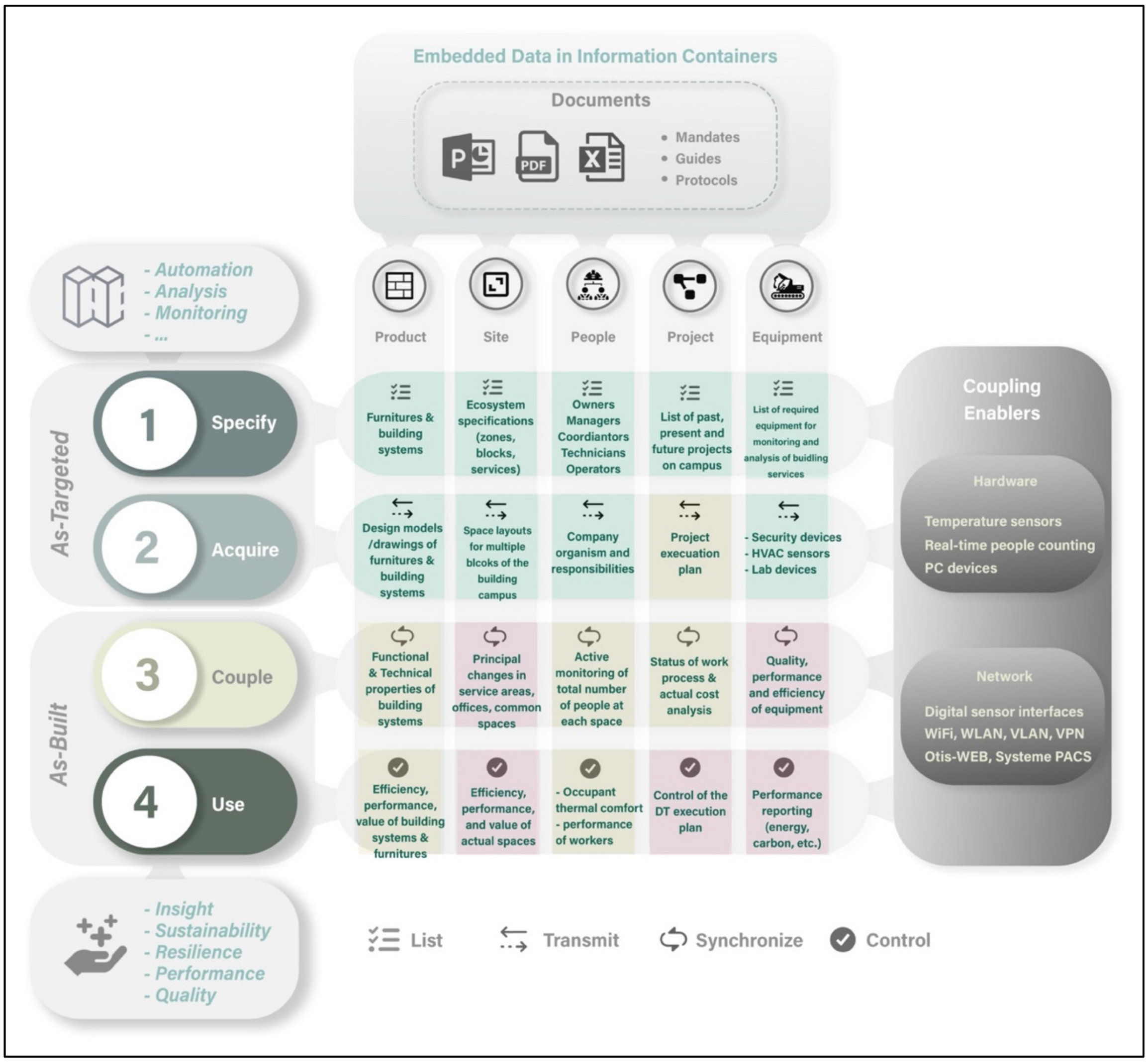


Figure 4.2 Implementation of the coupling action instantiation framework in case study 02

## 4.3 Chapter summary

This chapter reported the main findings from implementation of research constructs in the selected case studies. Despite the fact that both case studies were ongoing projects with different contexts and approaches, it was found that the taxonomy of lifecycle information coupling of built assets and resources can assist stakeholders in identifying coupling purposes and coupling outcomes of their projects. This was particularly evident in the case of high rise building where the identification of coupling purposes, outcomes, and actions were critical for the implementation of a DT.

The evaluation of the coupling action instantiation framework in both case studies revealed that multiple dispersed deliverables embedded in information containers can potentially be linked to proposed data categories and then used to generate Information Couples. This was found to be highly essential for the case of the bridge due to a large volume of uncoupled lifecycle information between the bridge and its digital replica in the simulated models and documents. In the case of the high rise building, the implementation of the framework resulted in the coupling of actual physical assets (e.g. spaces, building operation systems, etc.) with actual digital assets (e.g. digital documents). Maintaining such alignment with a higher level of coupling can result in the formation of a desired Asset Couple in order to support various aspects of a DT.

# CHAPTER 5

# DISCUSSION

This chapter interprets the results taken from case studies and bridges them to the existing body of knowledge in the context of lifecycle information coupling of built assets and resources. First, the key findings of research are summarized and linked to initial research question. Second, the findings are placed in context of this research along with implications and alignments with previous studies. Third, limitations and future of the work are outlined. Finally, a summary of discussions is provided along with potential follow-up research studies.

## 5.1 Discussion on the research constructs and the key findings

The taxonomy of lifecycle information coupling of built assets and resources, and its coupling action instantiation framework were proposed in the research to investigate required constructs, principles, and mechanisms to operationalize asset coupling in the built asset industry. The developed taxonomy as the main artifact of this research provided key dimensions and characteristics of asset coupling. The artifact moved beyond the organizational aspects of lifecycle information management. Indeed, it supports the integration of existing theories and concepts from multiple topics such as digital representations, digital twinning/threading, and traceability of assets and resources. In both case studies, the proposed dimensions of the taxonomy were implemented using coupling action framework, and their efficiency, effectiveness, and efficacy were assessed under various project phases, settings, and contexts.

The primary observation drawn from selected case studies was the presence of a large volume of dispersed data collected from physical assets and embedded in digital information containers with no specific links or real-time updates. This was interpreted as a failure to adopt an integrated approach to couple physical and digital built assets and resources across lifecycle stages, as well as a lack of effective collaboration among stakeholders to homogenise and link such data. Consequently, the implementation of coupling actions, particularly in the case of the bridge, was mainly associated with deliverables lacking updated information about the existing condition of actual bridge after monitoring activities and inspections. In this case study, the sensors and adopted network system were greatly served at providing data about structural behaviours of structural members against thermal changes. By coupling of monitored data with digital deliverables, stakeholders can use such coupled information to reduce a significant amount of time and work on inspection of all structural members at different period of time. Therefore, the proposed coupling mechanism provided a chance to integrate and link all dispersed data within shared information containers and link them to defined coupling actions for establishing effective Information Couples such as Deliverable Couples and Resources and Methods Couples.

The evaluation of the coupling action instantiation framework also demonstrated that the CLevel between physical asset and their digital representation in the virtual space was relatively poor in both case studies. This observation was made due to lack of semantic relationships between digital assets (e.g. Revit models or structural CAD drawings) and their corresponding actual physical assets. As described in the literature review of this thesis, digital representation of physical asset is a common requirement of asset coupling which can be supported by simulation techniques and methods. In both case studies, such requirement was only limited to representation of information in 2D drawings or generic architectural 3D model which were ranged from LOD 100 to LOD 300. For example, in case of the bridge, it was found that coupling of as-built building systems and as-built digital models with detailed simulation (LOD 400 and above) was necessary to analyse and optimize potential circular solutions for the renovation process.

Another important observation was the importance of the taxonomy to organize the body of knowledge and provide necessary information for planners, managers, and decision makers. This was evident in the case of the high rise building, where development of a DT required systematic organization of existing concepts, theories, methods, definitions, terms and etc. The proposed taxonomy was implemented in phase 1 of this case study, which enhanced interpretation of potential coupling purposes and outcomes for the development of a DT. In addition, defined coupling actions enlightened processes to be taken in order to achieve the desired situation. Using of proposed coupling mechanism was made identification of resources much easier to couple data collected from partner organization database (e.g. documents, interviews, workshops, etc.), literature reviews, and previous condition of the physical built assets. Therefore, the proposed taxonomy as a product of DSR, can be actively used in the early stages of asset management in order to enhance stakeholders decide what information needs to be deployed and operationalized for coupling of built assets and resources.

Furthermore, evaluation of taxonomy in the case of the high rise building showed that planning, monitoring and analysis were the most significant coupling purposes for improving the insight, sustainability, resilience, quality, and performance of the building in various management and operation practices. To implement a DT, a digital replica of the building should be facilitated with bi-directional coupling state by allowing data to be seamlessly transferred from physical to digital and vice versa. While Uni-directional coupling state is close to application of the DS, manual data flow from digital to physical may require more human involvement to ensure the accuracy and quality of processed data in real-world environment. In such cases, using the DoA metric may enhance stakeholders to assess functional automation between physical and digital assets. Indeed, automation of systems highly relies on taxonomies. Without taxonomies, it would be difficult to identify what would be required for automation purposes.

## 5.2 Contextualization of key findings

In response to ongoing trends towards digital twinning of physical and digital built assets, the proposed artifact did not aim to replace any given taxonomy in the context of CPS. Instead, it extended and framed existing concepts and theories into practice while addressing current asset coupling issues in the built asset industry. The proposed dimensions were built on the conceptual constructs of the LITE framework. Although some dimensions are ambitious, they are mostly aligned with current shift towards tight coupling of physical and digital assets. For example, evaluation results demonstrated that asset coupling was commonly constrained by failures to synchronize data bi-directionally in a real-time manner. While Information Couples are expected to acquire and process data seamlessly and in real-time, the status of physical and digital assets was most often updated in near near-time manner particularly in the case of the bridge.

Based on the literature review, it was observed that many researchers and practitioners have attempted to express their own understanding of digital twinning thorough conceptual models or frameworks. In this research, the proposed artifact was developed based on various pieces of knowledge that were overlooked in the context of CPS and DT. Unlike previous studies, the developed artifact aimed at characterizing all potential lifecycle information couples, whereas previous studies were mainly focused on Assets Couples which implies the concept of DT in the built asset industry. Thus, other Information Couples were further developed to potentially couple lifecycle information related to purposes, deliverables, and resources and methods. Indeed, the application of the proposed taxonomy and its instantiation framework convey various information states of an asset's lifecycle, from intent to deliver an asset until its reuse or decommissioning. This was found to be very important during implementation of the taxonomy when selected case studies were at various lifecycle stages.

Another contributing factor of the artifact lies in its full potential to support decision makers in management of physical and digital assets across lifecycle stages. While a large volume of data may be generated by different parties across an asset's lifecycle, adoption of the proposed coupling actions allows stakeholders to make decisions based on transparent, accurate, and trustworthy information. This was mainly observed in the cases of the bridge and the high rise, where a large volume of historical data (e.g. protocols, mandates and guides) was decentralized and embedded in multiple information containers. As discussed in section 1.5.2, a common barrier to implement information traceability of the built assets was information gap among multiple stakeholders. Such information gaps are critical to be closed by implementing the proposed coupling mechanisms and disclosing the meaningful information to decision makers.

Lastly, digital representation of physical and digital assets was found as an integral part of the asset coupling to bridge the information gap between real systems (e.g. tangible building components) and their virtual replica (e.g. intangible object in a parametric model). Observations from the case of the high rise building revealed that any virtual work (e.g. simulation) should be initiated at the early design stages of an asset's lifecycle because. In the case of existing built assets such as the bridge, simulation is very difficult because an extensive amount of historical data should be collected, analyzed and pertained before the simulation work. Therefore, it is essential to develop/acquire virtual models right after listing the asset's specifications and integrate them for the coupling action. At the end, such simulations would be frequently used by stakeholders to extract/view the coupled information during the O&M or EoL phases of the built assets.

## 5.3 Research limitations

As a nascent field of study, the literature review of this research was mostly limited to studies and works from other domains. For example, the notations of DT, DTH, and traceability systems are still regarded as new and potential solutions in the built asset industry while these concepts are actively evolving in other domains such manufacturing, aerospace, or food industry. Lack of adequate prior research on the topic, this study was required to develop new constructs for asset coupling which need to be further validated in the domain.

While data collection and coding of this study were mainly performed through literature reviews and observation of case studies, some data biases may exist. For example, some data related to emerging technologies, theories, frameworks, or models were excluded from data coding as they had not yet been published or finalised at the time of this study. This may makes some of the chrematistics of the taxonomy mutually exclusive which require further review to ensure their reliability. Time was another limitation for verifying the data collected from case studies as a few meetings and workshops were held with partner organizations and researcher participants. Therefore, further validations could be done by industrial experts or academic participants.

Regarding the selected case studies, some data were not available or accessible for comprehensive evaluation process. There were also some confidential data which required to be excluded form research results. While the scope of each case study was narrowed to address a specific issue, not all data pertaining to various aspects of assets and resources were available for evaluation of the taxonomy and its instantiation framework. Therefore, a validation roadmap might be needed to ensure the readiness and efficiency of the framework in various contexts and approaches.

## 5.4 Future works

The main opportunity for future work is to fully implement and validate the proposed taxonomy and its coupling action instantiation framework. While evaluation of developed constructs was performed internally using limited data sources, there exists many other evaluation methods that can be adopted to validate all dimensions, mechanisms, and principles of asset coupling. With the use of representational and functional metrics, an action research evaluation method could potentially test the principles of coupling actions in various fields of built asset industry. Indeed, the main implementation of taxonomy was limited to evaluation of vertical couples (e.g. intents couple, resources and methods couple). Whereas horizontal couples (e.g. Assets Couple) can be further engaged as information uses in the field of CPS Thus, implementation of the taxonomy in different real-world settings can provide a variety of feedback from industrial practitioners and researchers, improving the usefulness of defined constructs across the domain.

Furthermore, the practical applications of coupling action instantiation framework can be developed in the form of a platform to operationalize data for various coupling purposes. For this, one contributing factor is consolidation of coupling mechanism under different circumstances. While the proposed coupling mechanism was deployed to link embedded data into matrix of coupling actions and data categories, the internal mechanism between coupling actions to form various types of information couples was remained uninvestigated. Such future work can be facilitated with more automated and augmented enablers such as data-driven technologies, AI-based predictive devices, ML automation tools, blockchain technologies, information viewers with tangible user interfaces and etc.

Last but not least, asset coupling as part of the LITE framework can be communicated with researchers and practitioners to be further promoted and outreached. Also, the proposed dimensions and their characteristics of taxonomy have the potential to be harmonized with existing open source platforms (e.g. BIM Dictionary, BIMe information uses) and standards. Meanwhile, developed constructs in this thesis should be first published through targeted scientific papers and then be further developed, calibrated, and extended within academic and industrial communities.

### 5.5 Chapter summary

Overall, the key findings from evaluation of research artifact showed new opportunities to close the information gaps between physical and digital assets and resources through asset coupling. Such findings were further discussed and contextualized based on initial research questions and observations from cases studies and current literatures. This includes linking all embedded data across the asset's lifecycle and using them for coupling purposes, improving the digital representation of physical assets and resources, and providing stakeholders with coupled lifecycle information for better decision makings.

The proposed taxonomy and instantiation framework are intended to bridge the gaps in existing theories and concepts from various disciplines. While the proposed constructs may still have some limitations, they can be further extended, validated, and implemented by researchers and practitioners in order to meet their full potentials in the context of built asset industry. A number of future works were also suggested to address limitations of this research. These suggestions require active communication with academic and industrial communities through targeting publications, presentations, and etc.

# CONCLUSION

This thesis aimed to identify effective solutions for addressing current issues and gaps in the lifecycle information coupling of physical and digital built assets and resources. For this purpose, the current state of physical and digital coupling was reviewed through the lens of representation theories and lifecycle information management. Based on the literature review, it was found that the existing studies and efforts are encouraging a tight coupling between physical and digital assets. However, the key principles, constructs, and mechanisms that enable such tight coupling are still missing and need to be defined and implemented in the context of built asset industry. Therefore, the main objectives of the research were set to define, operationalize, and instantiate the concept of asset coupling in the built environment.

To investigate potential solutions, DSR methodology was adopted to formalize a research artifact based on the conceptual and extendible components of the Lifecyle Information Transformation and Exchange (LITE) framework. In addition, an open coding and classification framework was used to collect and analyse meaningful data from the existing studies and practices in the domain. To structure the body of knowledge and design the research artifact, taxonomical classification was identified as the main approach. While development of a taxonomy is a complex task, a systematic method was adopted to propose meta-characteristics and dimensions of the taxonomy. Moreover, a DSR evaluation method was used to design evaluation process of the research artifact using case studies of two real projects. For each case study, several activities were planned to evaluate the applicability, efficiency, efficacy and effectiveness of the research artifact.

A taxonomy of lifecycle information coupling of built assets and resources was proposed to identify what coupling dimensions and characteristics needed to conceptualize the asset coupling in the built asset industry. The taxonomy offered eight high-level dimensions covering various aspects of information coupling. The proposed dimensions were Information couples, Coupling States, Coupling Outcomes, Coupling Impacts, Coupling Actions, Coupling Metrics, and Coupling Enablers. The dimensions and their characteristics can serve to reduce complexity of asset coupling and allow stakeholders to unlock the value generated through integrated information management. It also supports effective implementation of digital information technologies across the asset's lifecycle.

In order to operationalise and instance the key dimensions of the proposed taxonomy, a coupling action instantiation framework was proposed as the design product of this research. The framework was articulated based on the dimensions of the taxonomy and main data categories that organize meaningful data for coupling actions. Moreover, a coupling mechanism was developed to extract data from potential information containers and link them to as-targeted and as-built coupling actions. This mechanism functioned as a matrix for integrating data with four defined coupling actions and coupling enablers to generate various types of Information Couples across lifecycle stages.

Evaluation of the proposed taxonomy and its instantiation framework demonstrated that a large volume of dispersed data collected from physical assets (the bridge and the high rise building) can be potentially harmonized and coupled with their digital assets at different information states. Systematic organization of such data and coupling them with physical assets can improve the collaboration between parties and allow stakeholders to make more informed decisions about actual condition of the asset.

Using the characteristics of the taxonomy can also help decision makers to identify what data needs to be coupled form the early stages of a project. This results in better management of information, reduction of time and cost during construction process, and effective extraction of data from as-built assets for reusability or recycling purposes. Lack of semantic relationships between digital representations of the physical assets was another observation that could be addressed through the development of accurate simulation-based models that are tightly coupled with their corresponding physical assets. To support this, various AI, ML, and Blockchain based technologies can be deployed to couple each component of an asset with their digital replica in the virtual space.

Even though the evaluation of research artifact was performed using two case studies with different approaches and lifecycle stages, it can be applied to other types of projects focusing on information coupling between physical and digital built assets and resources. The proposed taxonomy and its instantiation framework are conceptual constructs that need to be further implemented and validated by experts in other contexts and disciplines. As such, the next steps are to extend the key constructs of the taxonomy and identify various information uses for dealing with the existing coupling issues in the lifecycle information management of built environment.

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