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Lifecycle information transformation and exchange for delivering and managing digital and physical assets

Bilal Succar[a,*], Erik Poirier[b]

[a] ChangeAgents AEC, Founder of BIMe Initiative, Australia
[b] École de Technologie Supérieure, Montréal, Canada

A B S T R A C T

The rapid pace of digitalisation within the Construction Industry and the divergence from traditional practice inherent to this transformation requires the development of new knowledge to frame these emerging practices. Acting on increasing digitalisation pressures, many national and international standards, protocols, and specifications have been generated with little conceptual framing or with no theoretical underpinning. This positioning paper responds to practical business needs of organisations and project teams, builds upon existing conceptual constructs, and delivers a modular information management framework. The *Lifecycle Information Transformation and Exchange* (LITE) framework is an extendable conceptual skeletal for defining, managing, and integrating project and asset information. Developed, described, and explained for ongoing field testing, the LITE framework integrates multiple components - information statuses, states, milestones, flows, gates, routes, loops, actions, sets, and tiers – which collectively lay the foundations for an open access digital platform being developed by an international Community of Research and Practice. The framework describes – and aims to predict - information flows across an asset's lifecycle. Its modular conceptual structure, iterative flows, and task-oriented terminology are calibrated to guide the integrated design, delivery, and utilisation of assets of any type, function, or scale.

1. Introduction

1.1. Background

The adoption of advanced technological solutions is accelerating across the Construction Industry, and the broader sectors responsible for designing, delivering, managing and maintaining the built environment. This provides increased opportunities to address the industry's characteristically poor performance and lagging productivity. Reaping the full benefits of technological innovation, however, cannot be fully achieved without parallel innovations in processes and policies. When addressing lifecycle information management challenges in particular, there are many lessons to be learned from the Manufacturing and Software industries and significant benefits to be reaped from adapting their Lean, Agile and integrative production methods [1–3]. However, the distinctive challenges faced by the industry– especially lack of integrated supply chains [4–5] and discrete/fragmented information flows [6] – only permit partial adaptation of these methods [7–11].

To address distinctive and novel challenges, equally distinctive and novel solutions need to be sought. This paper responds to this challenge by introducing the Lifecycle Information Transformation and Exchange (LITE) framework, a conceptual structure that lays the groundwork for a new approach to asset and project lifecycle information exchange and management. The framework *accounts for* the proliferation of technological innovations enabling the integration of asset lifecycle information– e.g. Smart Contracts [12–14], Robotics [15–17], BIM Data Analytics [18], and Artificial Intelligence [19–20] into Design, Construction, and Operation activities ([21], Table 4). While presenting *new concepts* that intersect with mainstream discussions, and promoting *new approaches* that may seem to contradict those currently accepted by industry, is undoubtably challenging, the opportunities and benefits from potentially identifying more effective solutions may far outweigh potential adoption obstacles [22].

1.2. The need for the LITE framework

There are numerous ongoing efforts to formalise the business processes and project/asset information management practices of the Construction Industry, especially during the design and delivery phases of a built asset. These include the significant efforts by the International Standards Organisation [23] and the European Committee for Standardisation (CEN) which - supported by buildingSMART International [24] - have released a plethora of reference documents cited throughout this paper. The most notable release in recent years, and covering digital information management for the built environment, is the adaptation of the United Kingdom's Publicly Available Specifications (PAS 1192 series) as ISO 19650 suit of standards. These and other standards

* Corresponding author.
E-mail addresses: bsuccar@changeagents.com.au (B. Succar), erik.poirier@etsmtl.ca (E. Poirier).

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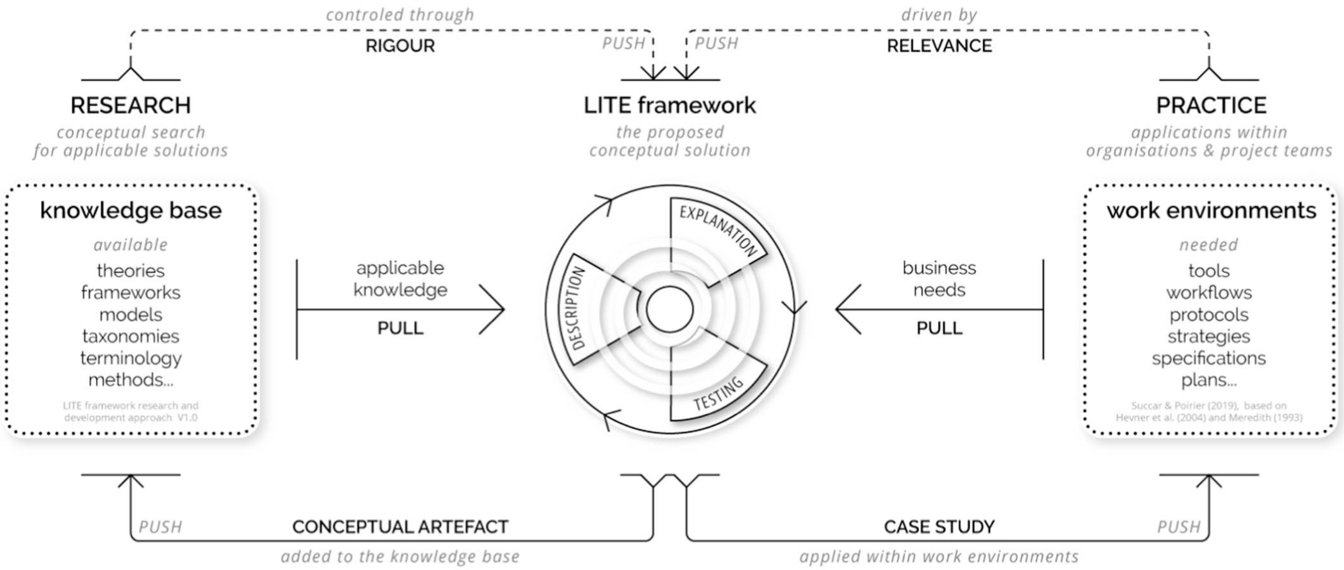

Fig. 1. LITE framework research and development approach (larger image) - adapted from Meredith [30] & Hevner et al. [44].

(e.g. ISO 12006, ISO 12911, ISO 16757, ISO/DIS 21597, ISO/DIS 23386, ISO/DIS 23387, ISO 29481, and DIN 91391) provide guidance for information management practices, software application development, collaborative working, and digital project delivery.

While these standards exert positive influences by promoting common structured practices in a notoriously unstructured domain (e.g. harmonising data exchange and minimising process confusion), they can also negatively impact process innovation (e.g. by increasing barriers to entry and codifying obsolete technologies) [25–27]. Foundational questions remain as to what should or should not be standardised in the fast-evolving domain of construction technologies and, more consequentially, questions relating to the appropriateness of these standards for information integration between overlapping domains. For example, a contradiction exists between the product-oriented information modelling standards for the Manufacturing Industry and the process oriented/project-based information modelling standards aimed at the Construction Industry [28]. As these two domains start to overlap (e.g. through prefabrication and large-scale 3D printing), the gap between the two standardisation approaches becomes difficult to efficiently bridge. These are but a sampling of arguments supporting the need to develop higher-level constructs that can better promote process innovation and enable information integration across domains.

According to [29], the Construction Industry, as a field of study, has very little in the ways of theoretical foundations. There is ample space for new theories, models and conceptual frameworks to investigate complementary solutions to the industry's information delivery and management challenges. A new framework, similar to the one proposed in this paper, is a theoretical proposition, and for it to be accepted as a valid conceptual representor or predictor of reality, it needs to be aptly *described*, adequately *explained* and comprehensively *tested* [30] over time and under different operational models. Also, for a framework to *continue to reflect* process innovations and to benefit from emerging information integration opportunities, this round of description, explanation, and testing must be iterative. Only when the framework and its embedded conceptual constructs are kept open, accessible, and adaptable can the theoretical proposition survive the relentless onslaught of transformational change and persist as a valid representation or predictor of reality. Delivering such a theoretical proposition for testing and verification, and offering its conceptual componentry for continuous improvement by other researchers, are the main objectives behind this paper.

While many frameworks exist that cover project-, product-, and asset- lifecycle information management within the Construction Industry - e.g. [31–37], the LITE framework introduced in this paper has a distinct and extrinsic aim: to enable the development and delivery of an *open access* digital platform for information management across a project and asset's lifecycle. For this platform to be communally developed, continuously extended, and professionally tested, its terms, classifications, taxonomies, and underlying conceptual models need to be exposed for peer-review and ample scrutiny.

1.3. Methodology

The development and instantiation of the LITE framework lies within the realm of design sciences and is guided by tenants of Design Science Research (DSR). As will be demonstrated in Section B, the framework bridges different worlds - the physical and the digital, the natural and the social – as it attempts to both describe and explain how information systems and information management practices work. In doing so, the LITE framework aims to prescribe a solution that predicts outcomes of both academic relevance and industrial practicality.

Design Science Research is embedded in the *sciences of the artificial* and thus deals with “knowledge about artificial objects and phenomena” ([38], p. 3). As a research methodology, it has gained significant traction in computer science, software engineering, and information systems research where the development *and* application of practical technological artefacts have been a research priority for decades [39]. As there are many parallels between information systems and construction projects [40], the DSR methodology is highly-relevant for construction research. It offers an iterative, constructive, and pragmatic approach [41] and allows simultaneous building and evaluation of artefacts. These artefacts, according to March and Smith [42], can be either [i] Constructs, the basic language of concepts used to characterise phenomena; [ii] (conceptual) Models, the combination of constructs used to describe tasks and situations; [iii] Methods, the ways of performing goal-driven activities; or [iv] Instantiations, the physical implementation intended to perform certain tasks. In this respect, and key to the pursuit of a framework as a means to deliver an online platform, DSR supports the creation - through rigorous research - of Products that serve human purposes [42–43]. These products are the *technological rule*, the “chunk of general knowledge linking an intervention or artefact with an expected outcome or performance in a certain field of application” ([43], p. 23).

Fig. 1. illustrates the methodology for researching and developing the LITE framework. It represents an amalgamation of the *Design Science Research Cycle* introduced by Hevner, March, Park, and Ram [44] and the *Normal Research Cycle* introduced by Meredith [30] ([45],

Fig. 3).The DSR cycle balances the *relevance* and *rigor* of the artefact being developed (the LITE framework) as it responds to the *pull* from both practice (i.e. the business need for an asset lifecycle information management solution) and *from research* (i.e. the knowledge base of existing theories, frameworks, models, and similar constructs). This is *driven by relevance* for practitioners in their work environments (i.e. the potential usefulness and usability of the LITE framework by organisations and project teams) and *controlled in a rigorous* manner by researchers (i.e. the rigorous research to develop knowledge supporting applicable solutions). As the artefact is developed – through iterative rounds of description, explanation, and testing - it can be concurrently applied in practice and fed-back (pushed) into the knowledge base through case studies, structured interviews, and similar (detailed in the "Completed Development and Validation Rounds" subsection). Provided it continues to respond to business needs and to be rigorously controlled for research quality, these push/pull dynamics and iterations will allow a *valid and relevant* LITE framework to be further developed, extended, and improved.

The principle challenges in conducting this and similar research is to balance the *relevance* of the research outcome with the *rigor* of research process [46]. To achieve a sustainable balance, and following the principles discussed in March and Smith [42], Hevner et al. [44], Järvinen [47], and Van Aken [43], the LITE framework has undergone multiple development and validation rounds and will continue to undergo these rounds as the research and development process continues.

The initial development stage offered a description and an explanation of the phenomena at hand: new constructs were identified and *described* through a process of retroduction, conceptual clustering [48], and reflective learning [49,50]. The development was both retrospective and prospective to identify: what are the elements that characterise asset information exchange within the Construction Industry? How do these elements operate and evolve across a built asset's lifecycle? How are they impacted by emerging tools and technologies? And what underlying information management processes need to be developed in order to cope with the rapid pace of innovation and the transition towards 'digital by default' practices? These constructs were then assembled into a framework (a hypothetical model of reality) that visually *explains* information events, and delivers a *testable* theoretical proposition reflecting what has been described and explained.

The development of the artefact followed a *retroductive* approach, a "mode of inference in which events are explained by postulating (and identifying) mechanisms which are capable of producing them […]" ([51], p. 107). Retroduction deploys "creative imagination and analogy to work back from data to an explanation" and involves the "building of hypothetical models as a way of uncovering the real structures and mechanisms which are assumed to produce empirical phenomena" ([52], p. 25). In constructing such hypothetical models, ideas are "borrowed from known structures and mechanisms in other fields" ([53], p. 2) and theoretical explanations for specific observations are considered when formulating hypotheses about the phenomenon under study [54]. The retroductive method as applied here shares many similarities with *abduction*, "a form of inference that goes from data describing something to a hypothesis that best explains or accounts for the data" ([55], p. 5). Retroduction follows a three-step approach - with the first two steps demonstrated in this paper - where "the research starts in the domain of [the] actual [empirical], by observing [experiencing] connections between phenomena [to explain events activated in the domain of the actual].The researcher [then] builds a hypothetical model, involving structures and causal powers located in the domain of real, which, if it were to exist and act in the postulated way, would provide a causal explanation of the phenomena in question. The third step is to subject the postulated explanation to empirical scrutiny" ([56], p. 635).

Diving a bit deeper into underlying theory, retroduction is a search to *understand and predict* event patterns and to establish causal links; both key components of the Critical Realist approach. Critical realism distinguishes between how individuals view the world and how the world empirically exists, and assumes that both exist independently [51]. Knowledge of the world is thus socially constructed and is in constant flux. The role of the critical realist is to discover "the underlying structures that generate particular event patterns"([57], p. 7), the generative mechanisms, the relations, and the causality [58]. Fittingly, this study adopts the critical realist perspective as, on one hand, it aims to answer the question 'what causes specific events to happen?' ([59], p. 121) and, on the other hand, it asks 'how can these events be improved?' thus embodying the pragmatic and prescriptive perspectives of DSR. That is, critical realism's wider construction of 'truth' expands DSR's ability to find utility and enables the development of more robust artefacts.

By providing an epistemic and ontological framework, critical realism offers a solid foundation to investigate a phenomenon as complex and multifarious as asset lifecycle information management [57]. The notion of causality here is important for the LITE framework to serve its intended purpose. Critical realism not only accepts causality but makes it a central feature in providing a framing of the world [60]. As a topic worthy of a separate investigation, only a few Construction Industry researchers have adopted a critical realist perspective – e.g. Smyth and Pryke [61] studied collaborative relationships, Smyth [62] focused on trust, and Fox [63] looked intently into BIM adoption. Apart from these researchers and a handful of other studies, applying the critical realist perspective to investigate the Construction Industry is still sparse and not widely adopted.

1.4. Terminology

This study relies on many terms that are either (a) adopted from international standards; (b) adapted from evolving industry specifications and protocols; or (c) newly minted to represent novel concepts and their relations [64]. The decision to adopt, adapt, or mint each term is made deliberately to ensure alignment with previously published research and minimisation of semantic conflicts with national/international standards.

All the key terms employed throughout this paper revolve around the concept of 'information': its types, uses, flows, activities, and actors. Information here refers to the "*facts provided or learned about events, things, processes or concepts that has a particular meaning within a certain context*" [65] [adapted from the Oxford Dictionary [66] and ISO/IEC [67]]. Other relevant definitions[1] include "*meaningful data*" [68] and "*message used to represent a factor or concept within a communication process, in order to increase knowledge*" [69]. In the context of an asset's lifecycle, information can be subdivided into *Unstructured* and *Structured Information* [70–72]. Unstructured Information refers to data that "does not have a pre-defined data model or is not organised in a pre-defined manner" [73], as well as undocumented, and temporary information (e.g. hand sketches and casual phone chats); and Structured Information (the focus of this study, referred to as only 'information' hereafter) is the computable data that can be transformed to/from varied states and exchanged between actors throughout an asset's lifecycle.

To allow the generation of a new information management framework covering the whole asset lifecycle, the terms 'information' and 'asset' are either qualified or subdivided into smaller formative parts. These formative parts are then combined with other concepts to deliver new denotations:

➔ The term 'information' refers to *both* 'static' and 'dynamic' information and can be qualified as *either* 'targeted' or 'actual'. This

[1] There are 78 definitions of the term "Information" within ISO (as of July 2018) including four that are specific to the 'Building and Construction' sector. Please refer to https://www.iso.org/obp/ui/#search

subdivision allows for the comparison of *targeted* deliverables with *actual* deliverables, and measuring *needed* resources and methods against *available* resources and methods;

➔ The term 'asset' is qualified to be either *digital* and/or *physical*. This allows the management of assets as they exist in either or both manifestations. This approach is especially needed as – due to the increased availability of mixed reality solutions [74] [75] - the line separating what is *virtual* from what is *real* continues to blur;

➔ The term 'information requirements' - prevalent in numerous international standards, industry guides, and national specifications – is replaced by two complementary terms: 'Targeted Deliverables' (digital or physical assets) and their respective 'Needed Resources and Methods'. As discussed by Rodhain and Fallery [76] and Cavka, Staub-French, and Poirier [77], identifying information requirements of specific actors (e.g. a client organisation) is inherently difficult as actors may be (a) *unwilling* to express their requirements, (b) *unaware* of their requirements, or (c) *unable* to express their requirements in a clear and actionable manner. By replacing 'Information Requirements' with the two complementary terms, a clear distinction is made between the expected outcomes (Targeted Deliverables) and the methods and resources needed to achieve them (Needed Resources and Methods);

➔ The term 'Information Transformation' is used to describe the continuous two-way morphing of information: from *expected* deliverables into *actual* assets, and from *digital* assets into *physical* assets, and vice versa. The term should not be confused with legacy Construction Industry theories discussing the transformation of inputs into outputs [8,78];

➔ The term 'demand organisation' [79], 'appointing party' [80], and 'employer' – where needed – are replaced with 'Demand Entity' to increase scalability. A Demand Entity and its counterpart, the 'Supply Entity', could represent an organisation, an individual, or a non-human information *actor*. In this respect, this study follows the Actor-Network Theory (ANT) and does not discriminate between human and machine actors [9]. According to Müller and Schurr [81], "ANT treats humans and nonhumans as completely symmetric and effaces any difference between the two [82]";

➔ The term 'design, construction, and operation', typically used to delineate Project Lifecycle Phases, will alternate with the term 'design, delivery, and utilisation' which offers a broader coverage of lifecycle phases for both physical *and* digital assets;

➔ The term 'information' – when used to describe Digital Assets - can be subdivided into three Information Representation Types or 'digital artefacts': documents, models, and data – subdivision first introduced in Succar, Saleeb, and Sher [83]:

➔ Document: A medium (e.g. an email, web page, or a PDF document) carrying a variety of information including text, metadata, or embedded 3D models. A document refers to "*information and its supporting medium*" [i.e. when the information is placed within a medium, it becomes a document] …."*the medium can be paper, magnetic, electronic or optical computer disc, photograph or master sample, or a combination thereof*" ([84], Item 4.5), adapted from ISO [85]. In this study, the term Document will refer to a *digital* medium or an *analogue* medium to be digitised in preparation for management and utilisation. When referring to non-digital documents, the term will be qualified (as in *paper* document). Examples of Documents include a Master Plan Drawing, a Performance Certificate, and an Audit Report;

➔ Model: A "*representation of a system that allows for investigation of the properties of the system*" [86]. As a term, it may refer to digital models (e.g. shell/boundary or solid geometry graphical models); physical models (e.g. a sandcastle, LEGO model, or 3D printed shapes); or financial, mathematical, and conceptual models. In this study, unless qualified, the term Model will refer to a three-dimensional digital medium carrying a variety of information and – potentially - embedding or referencing both Documents and Data sets. A Model can represent a discipline/specialty (e.g. architectural model), a state (e.g. record model), or a base technology (e.g. object-based model); and

➔ Data: A digital sequence of symbols – typically letters and numbers - that can be collected and parsed/interpreted by an actor. Data may be statically *embedded* within Documents and Models or *drive* their dynamic generation/modification - adapted from ISO/IEC [87]. Data can be captured through sensors, actuators, and scanners [88]; derived from connected data sources; or generated through machine learning. The term Data may be coupled with other terms preceding it (e.g. *structured*, *unstructured*, or *meta*-Data) or following it (e.g. Data *cloud*, *object*, *routine*, *script*, *set*, or *table*) to indicate either functional groupings, relationship structures, internal cohesion, semantic inferences, coded computer instructions, or 'as a variety of charts and diagrams' [89]. In this study, and unless qualified, the term Data will refer to digital computable data. Data sourced from analogue devices (e.g. liquid thermometers and legacy imaging equipment) need to be digitised before it can be utilised and managed.

This representational subdivision is *utilitarian* and is intended for practical purposes: allow more accurate identification of targeted digital deliverables (refer to "Information Milestones") and – as illustrated in the Information Taxonomy (Table 1) – provide flexibility in specifying information delivery *uses*, *views*, *view definitions*, *viewers*, and *environments*.

The subdivision of information into physical and digital, and the subdivision of digital information into representational types can only be delineated relative to the information actor. What is 'physical' or 'tactile' to a one actor may be experienced as 'digital' by another actor. Also, what is perceived or consumed as 'modelled information' by one actor, may be accessed as 'structured data' tables by another. Moreover, the three types of artefacts – documents, models, and data - are not mutually exclusive: a digital document embeds data/metadata and may also embed an interactive 3D view (e.g. a 3D PDF document); a digital model may embed schedules and live data streams; and a data set may describe the geometry of a 3D model or the content/style of a document. Finally, documents and data sets may be extractions from a 3D model and 3D models may be extractions from documents and data sets (e.g. models generated automatically from 2D drawings).

Despite the lack of mutual exclusivity between the three representational types, these subdivisions are nonetheless useful for increasing the *purposefulness* of information generation and flow. For example, a Demand Entity can employ these subdivisions to specify its informational preferences or priorities: demand the delivery of digital assets as data sets fed directly into its data management system; specify the exclusive delivery of object-based models for use in prefabrication; or request a specific combination of the three representative types to satisfy evolving contractual obligations.

2. The LITE framework

The Lifecycle Information Transformation and Exchange (LITE) framework is composed of numerous conceptual components that need to be understood independently and collectively. Acting as a visual summary, Fig. 2 overlays many of these components and illustrates the relations between them. Each subsection below explains a key component and offers a simplified visual rendition of its concepts:

Fig. 2 summarises how information flows and transforms across an asset lifecycle. The image overlays visual representations of multiple conceptual components in a single Information Cycle:

1. Information Statuses describing information as it transforms from targeted (To Be) to actualised (As Is).
2. Information States describing information as it transforms from being a purpose (an intent), to a deliverable (a digital or physical asset), to a resource and method necessary to deliver the asset as intended.

Table 1
Information taxonomy[a] v2.0.

Information Use: The intended uses/applications of information		
Document Use The *intended* or *expected* types of deliverables from developing and exchanging information through Documents Examples: document-based reporting, certifying, or warranting	Model Use The *intended* or *expected* types of deliverables from generating, collaborating-on and linking Models to external databases Examples: model-based representing, simulating, or quantifying	Data Use The *intended* or *expected* types of deliverables from generating, exchanging, and manipulating Data Example: data mining or scripting (e.g. using code to drive cutting, milling or sintering equipment)
Information View: How information is represented to enable its use		
Document View A view enabling one or more Document Uses. A Document View can be a drawing, schedule, report, an instruction memo, or a set of specifications. A Document View may be drafted (computer-assisted) by a human-actor or derived automatically from a Model or Data source Examples: Product Data Sheet or Room Data Sheet (a drawing detailing an operator's requirements for each room type including room layout, furniture, fittings, equipment, and surface finishes)	Model View A view enabling one or more Model Uses. A Model View can be a static/ dynamic 3D view, an animation, or a holograph. A Model View follows the specifications within its corresponding Model View Definition or reflects custom project/asset requirements Examples: Model View showing only Architectural elements, or another showing both Mechanical and Structural elements within a Model Viewer (see further below)	Data View A view enabling one or more Data Uses. A Data View can be a code snippet, a Computer Numerical Control (CNC) file, an XML/JSON file, or similar Examples: a data chart, a node-link diagram, an If This Then That (IFTTT) recipe, an FME translator, or a visual script in Grasshopper or Dynamo
Information View Definition: How Information Views are defined for consistent use of information		
Document View Definition A specification (or template) which identifies the contents, attributes, and formats of Document Views (see above). Document View Definitions are typically generated by authorities, technology advocates, and associations promoting standardisation Examples: Product Data Template (a document identifying the information pertaining to a specified product - e.g. model, manufacturer, performance attributes, and maintenance requirements)	Model View Definition A specification which identifies the properties and specifies the exchange requirements of Model Views. A 'standardised' Model view Definition (MVD) can be a subset of an established schema (e.g. Industry Foundation Classes), typically intended for software developers (not end users) to implement into their Software Tools (ISO, 2016) Example: the IFC4 Design Transfer View by buildingSMART International	Data View Definition A specification which identifies the properties and specifies the exchange requirements of Data Views. Data View Definitions are typically generated by information actors to formalise data exchange scenarios and harmonise data analysis methods Examples: a data representation template, data translation script, or data analysis formula
Information Viewer: The software allowing access to information to human actors		
Document Viewer A software application allowing users to inspect and manipulate information according to pre-set Document Views Examples: PDF reader or 2D CAD viewer	Model Viewer A software application allowing users to inspect and navigate Models according to ad-hoc or standardised Model View Definitions Example: BIM Vision, BIMx, Dalux, or Solibri Model Viewer	Data Viewer A software application allowing users to inspect and manipulate data according to pre-set Data View Definitions Examples: Tableau or Business Intelligence tools
Information Environment: The distributed digital ecosystem allowing the collation and utilisation of information by multiple stakeholders. An Information Environment may include a combination of software solutions connected to disparate data sources through middleware and plugins		
Shared Document Environment An ecosystem for managing documents, composed of several software modules – including a Document Viewer, and allowing the filtering of information by Document View Example: A digital ecosystem built around a Document / Project Management System	Federated Modelling Environment An ecosystem for managing Models, composed of several software modules - including a Model Viewer, and allowing the filtering of information by Model View Example: A digital ecosystem built around a Model Server or BIM-enabled Software as a Service (SaaS)	Integrated Data Environment An ecosystem for managing Data sets and structures, composed of several software modules – including a Data Viewer, allowing the filtering of information by Data View Example: A digital ecosystem built around Data Warehousing and Data Integration solutions

[a] An earlier version of this table was published online on June 20, 2016 as the 'Project Information Taxonomy' [90].

3. Information Milestones describing the natural deflection points where information transforms from being an idea about an asset, to a digital representation of an asset, to becoming the physical asset itself.
4. Information Flows and Gates describing the flow of information throughout an asset's lifecycle and the mechanisms controlling these flows.
5. Information Routes describing the paths information follows depending on its degree of autonomy.
6. Information Loops describing the iterations information undergoes during the delivery, use and reuse of an asset.
7. Information Actions describing clusters of granular information activities and tasks to be completed to deliver, use and reuse an asset.
8. Information Shortcuts describing the valid reasons and potential risks of diverging from normative information routes.
9. Information Sets describing the document/module types for collating asset lifecycle information.
10. Information Tiers describing the information to be organised and shared through a Common Information Environment.

These conceptual components and their simplified visual renditions are individually explained below:

2.1. Information Statuses

The framework identifies two statuses for describing information as it continuously transforms throughout the information lifecycle: a Targeted Status representing what is intended, needed, planned, or expected; and an Actual Status representing what is realised, available, executed or measured.

Fig. 3 includes a horizontal *status transformation boundary* separating what is intended (i.e. To Be) above the line, and what is actual (i.e. As Is) below the line. Crossing the *dotted line* may be instantaneous and in one go, or a gradual/piecemeal transformation over time. Speed (how fast), duration (how long), and method of production/execution are

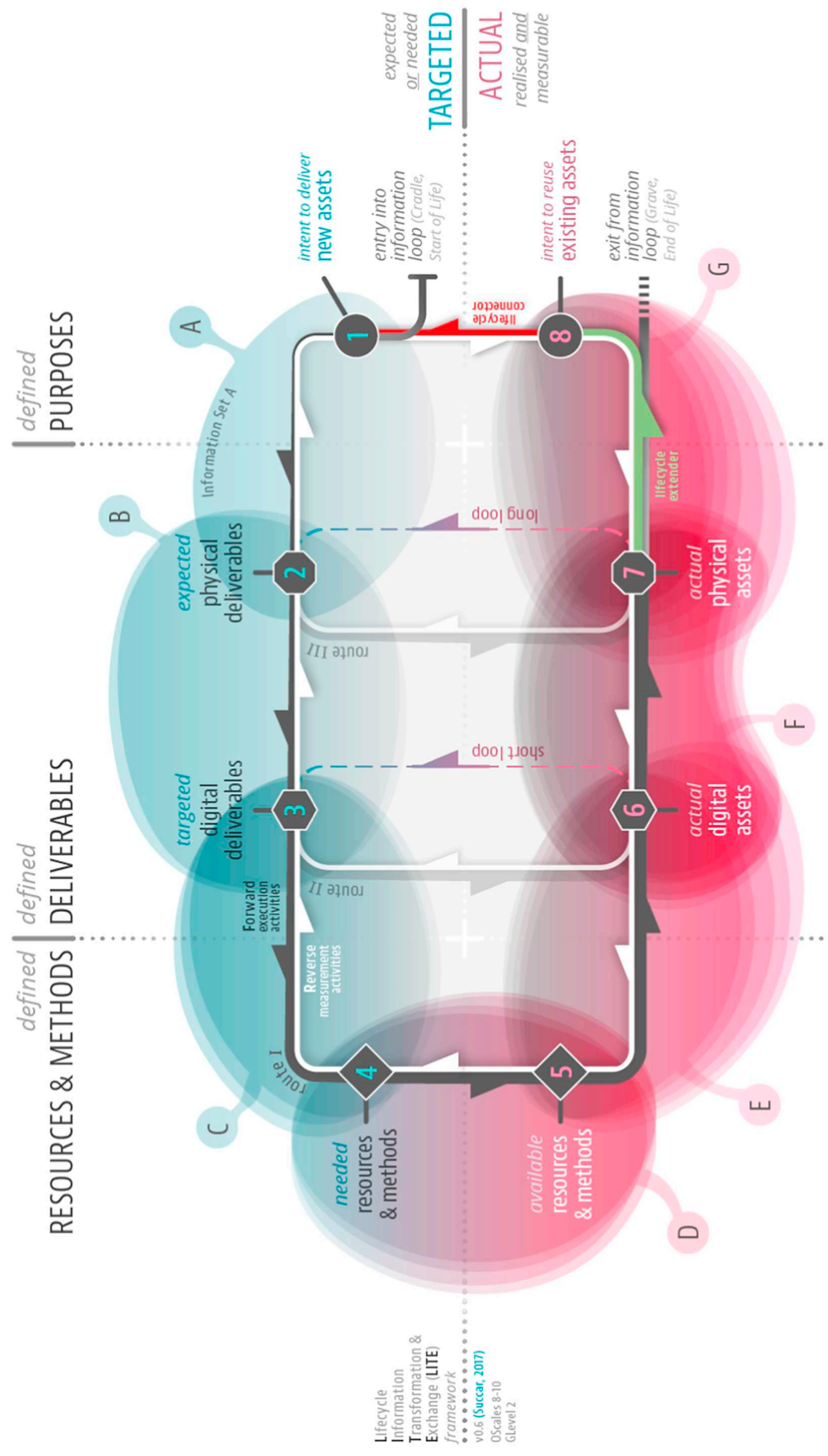

Fig. 2. The LITE framework – shown at GLevel 2 (larger image).

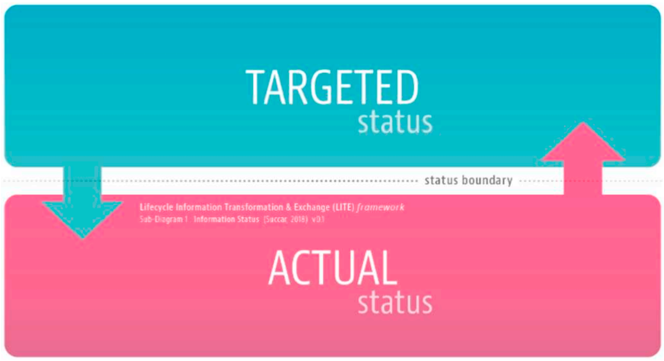

Fig. 3. LITE framework - *Information Statuses* (larger image).

examples of metrics that can be applied to understand, predict, or improve information transformation.

2.2. Information States

From the initial intent to deliver a new asset, until its decommissioning or reuse, the information covering the asset's design, delivery, and utilisation can be clearly defined and continuously updated. If managed properly, this information will not be lost as the asset transforms from being a mental construct, to being properly represented in digital formats, to finally becoming a tactile product or a physical space. The LITE framework captures this transformation and represents it as three Information States – Purposes, Deliverables, and Resources and Methods - separated by vertical *state transformation boundaries* (Fig. 4). Information within each State can be either Ad-hoc (ill-defined), Defined, Managed, Integrated, or continuously Optimised [91]. For information to efficiently flow between States, the information must be well *defined*:

2.2.1. Defined Purposes

Information covering 'purposes' is a compilation of the explicit reasons behind, the functions required, and the value sought (commercial, social, and/or environmental value) from procuring a new Physical Asset or operating/reusing an existing one. Purposes can be defined in many ways: through initiating an integrated set of specifications (refer to "Information Sets"); relying on project briefs – e.g. RIBA (2016); developing varied types of Information Requirements (IR) s - e.g. Organisational-, Asset-, and Project- Information Requirements - as defined in the ISO 19650 suite of documents; or through collating an asset's functional requirements, project's information benefits, and whole-of-life expected value [92–97].

Defined Purposes are either organisation-specific, project-specific, or market-specific. Organisation-specific Purposes are those internal to an organisation (e.g. meeting business objectives and aligning with organisational culture). Project-specific Purposes are those intended to satisfy explicit project requirements – Ends, Means, and Constraints [98]- in contracts and formal/informal agreements; and Market-specific Purposes are those intended to satisfy social, legal, and environmental obligations and the application of international or local best practices. Purposes are not mutually exclusive, and the same Defined Purpose may satisfy all three types - thus indicating 'critical alignment' between them.

2.2.2. Defined Deliverables

To enable the delivery and operation of all but the simplest Physical Asset, information captured earlier as *purposes* will need to be transformed into Digital Assets. During the early phases of an asset's lifecycle, Digital Assets can be defined through Information Uses - Model Uses, Document Uses, and Data Uses, later transformed into Models, Documents and Data sets, and – upon execution through construction, manufacturing, and assembly - transformed into Physical Assets. For deliverables to be properly managed – in both their digital and physical forms - they also need to be well *defined*. As two examples, model-based Deliverables can be defined using the Model Uses List [99] and the BIM Project Execution Planning Guide [100].

2.2.3. Defined Resources and Methods

Resources refer to the human and machine actors, as well as the physical, technical, financial, and other resources that need to be invested to transform a targeted deliverable into an actual one. Methods refer to:

- ➔ *Procurement methods* - e.g. Cost Plus or Lump Sum;
- ➔ *Scheduling methods* - e.g. Critical Path Method or Location Based Scheduling [101];
- ➔ *Project management methods* - e.g. PRINCE2 or PMBOK [102];
- ➔ *Production methods* - e.g. Lean Construction [103,104], Six Sigma [105], or Concurrent Engineering [106];
- ➔ *Information management methods* - e.g. Information Management Process in ISO 19650-2 [107]; and
- ➔ *Maintenance methods* – both reactive (e.g. Run-To-Fail) and proactive (e.g. predictive maintenance according to pattern recognition through Machine Learning) [108,109].

To properly manage these Resources and Methods, they similarly need to be properly *defined* and duly satisfied.

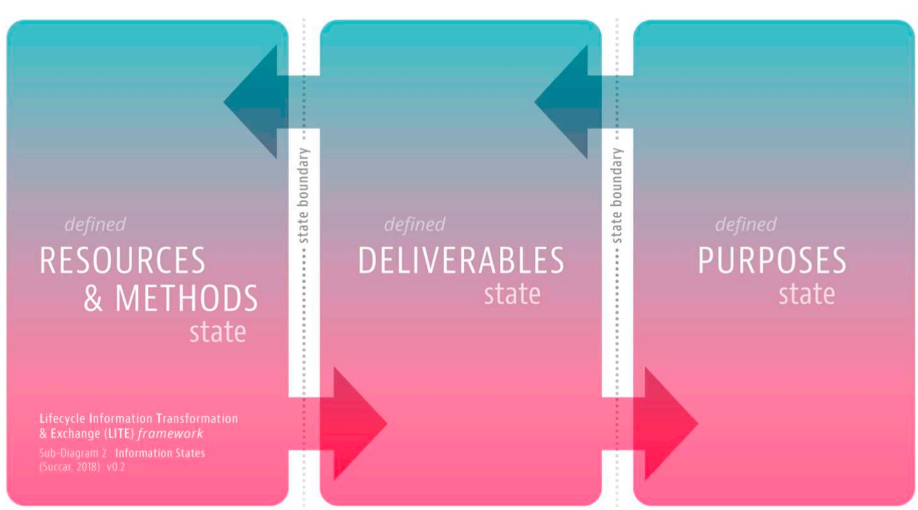

Fig. 4. LITE framework - *Information States* (larger image).

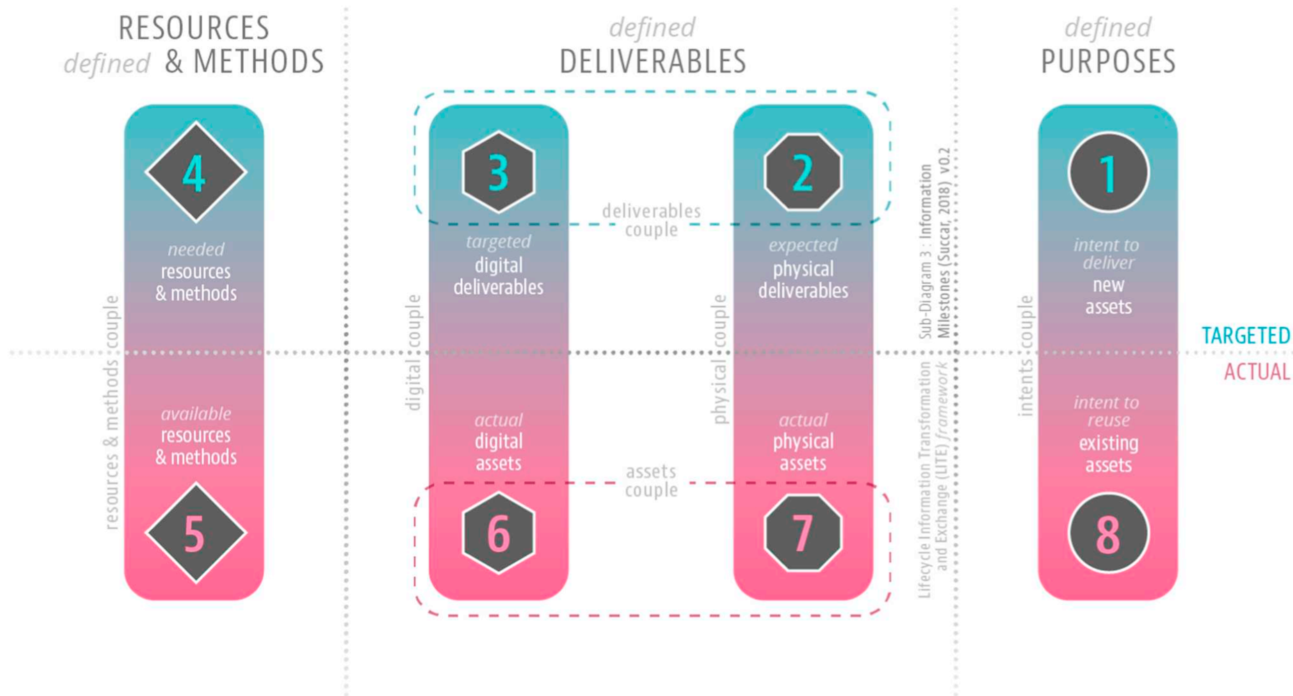

Fig. 5. LITE framework – *Information Milestones* (larger image).

The boundaries separating each State from another is dependent on the actor observing or experiencing these boundaries - what is a resource for one actor, is a deliverable for another. For example, a cement bag is a deliverable by the cement supplier and a resource for the builder. Moreover, what is a physical reality for an actor is a conceptual representation – or a virtual reality – for another. For example, a steel beam for a steel erector will be a 3D object or a shop drawing for a structural designer.

2.3. Information Milestones

The framework identifies eight Information Milestones that information traverses throughout an asset's lifecycle (Fig. 5). Each milestone is a manifestation of information as it transforms from being an idea about an asset, to a digital representation of an asset, to becoming the Physical Asset itself. There are eight milestones that reflect natural deflection points in information flow:

[1] Intent to Deliver New Assets
Information is expressed as an *initial exploration* of what new assets are needed, a *specification* of the general attributes of these assets, followed by the *explicit decisions* to conduct all activities *leading to the delivery* of these assets. The initial exploration may include general assumptions about the delivery scope, durations, risks, resources, and costs. This milestone is reached when a Demand Entity (e.g. a real estate developer, a parts manufacturer, or a roads' authority) decides to commission the design and/or delivery of new assets (e.g. a hotel complex, a car windshield, or a 100 km road section);

[2] Expected Physical Deliverables
Information is expressed as a set of spatial/geometric and functional attributes that define the Physical Assets and how they will be utilised. This milestone is reached when all functional and non-functional attributes of new assets (e.g. the brief covering hotel room numbers/types, or the performance metrics of both the windshield and road section) are clearly defined;

[3] Targeted Digital Deliverables
Information is expressed as a set of digital deliverables that need to be generated as to represent and simulate all attributes of the Physical Assets. This milestone is reached when the digital artefacts – the Documents, Models, and Data sets – needed for the design, delivery, and utilisation of the assets are clearly defined;

[4] Needed Resources and Methods
Information is expressed as a set of resources and methods that are needed to deliver the expected Digital and Physical Assets. This milestone is reached with the identification of what new *human actors* (their specialties and expertise), *machine actors* (software, hardware, and networks), and *methods* (explained in "Information States") are needed to deliver the asset as targeted;

[5] Available Resources and Methods
Information is expressed as the actual resources and methods to be deployed to deliver the expected Digital and Physical Assets. This milestone is reached with the forming of the work/project teams and the identification of actual resources and methods to be deployed towards delivering the assets as targeted;

[6] Actual Digital Assets
Information is expressed as Digital Assets representing - simulating, quantifying, and qualifying - the Expected Physical Assets. Digital Assets include 2D drawings extracted from 3D models (e.g. building sections and elevations), images, videos, records (e.g. maintenance records), reports (e.g. fire hazard report), logs (e.g. security access logs), and certificates/declarations of performance ([110], Table PM - Project Management) [111–114]. This milestone is reached with the successful delivery of all Documents, Models, and Data sets needed for the delivery of the targeted assets;

[7] Actual Physical Assets
Information is expressed as Physical Assets – whole facilities, systems, or components [115] – delivered to satisfy previously-defined expectations. This milestone is reached with the delivery and commissioning of the targeted assets; and

[8] Intent to Reuse Existing Assets
Information is expressed as an investigation into *how* existing assets are actually used verses the original intent from delivering them, and whether these asset – in part or as a whole - *can be* reused, refurbished, or recycled. This milestone is reached when the Demand Entity explicitly decides to redesign, renovate, reuse, recycle, or discard the existing assets.

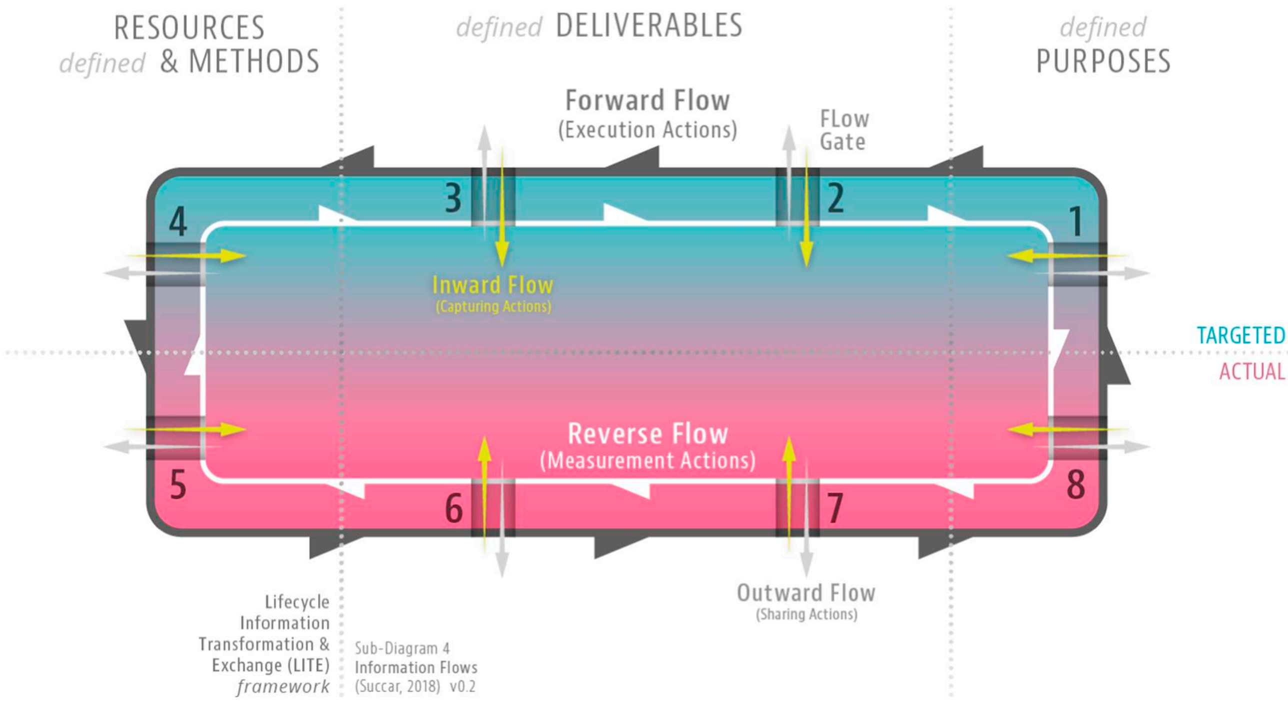

Fig. 6. LITE framework – *Information Flows* (larger image).

Fig. 5 also illustrates six Milestone Couples indicating their semantic proximity and the need to keep them *aligned* (minimum) or *synchronised* (optimum). There are four *vertical couples* connecting the *targeted* version of an Information Milestone with its *actual* counterpart: Purposes Couple [connecting milestones 1 and 8]; Physical Couple [2 & 7]; Digital Couple [3 & 6]; and Resources and Methods Couple [4 & 5]. For example, when Intending to Deliver New Assets [milestone 1], the Purpose for Existing Assets [milestone 8] needs to be evaluated. This is exemplified by (i) *validating* whether existing assets suit actual needs and purposes, (ii) v*erifying whether the existing assets* can be refurbished, recycled, or reused instead of investing in new assets; or (ii) *specifying* whether or not new assets are intended for future reuse - including how to reuse, how many reuses, and/or duration of reuse – which influences the definition of deliverables, and the selection of resources and methods deployed in designing and delivering these assets. This continuous checking of information deliverables – whether they are digital or physical – against what was originally targeted or expected would help in balancing *process efficiency* (e.g. reducing waste) with both *agility* (e.g. responding to continuous change) and *service effectiveness* (ensuring clients receive what they want, when they want it)

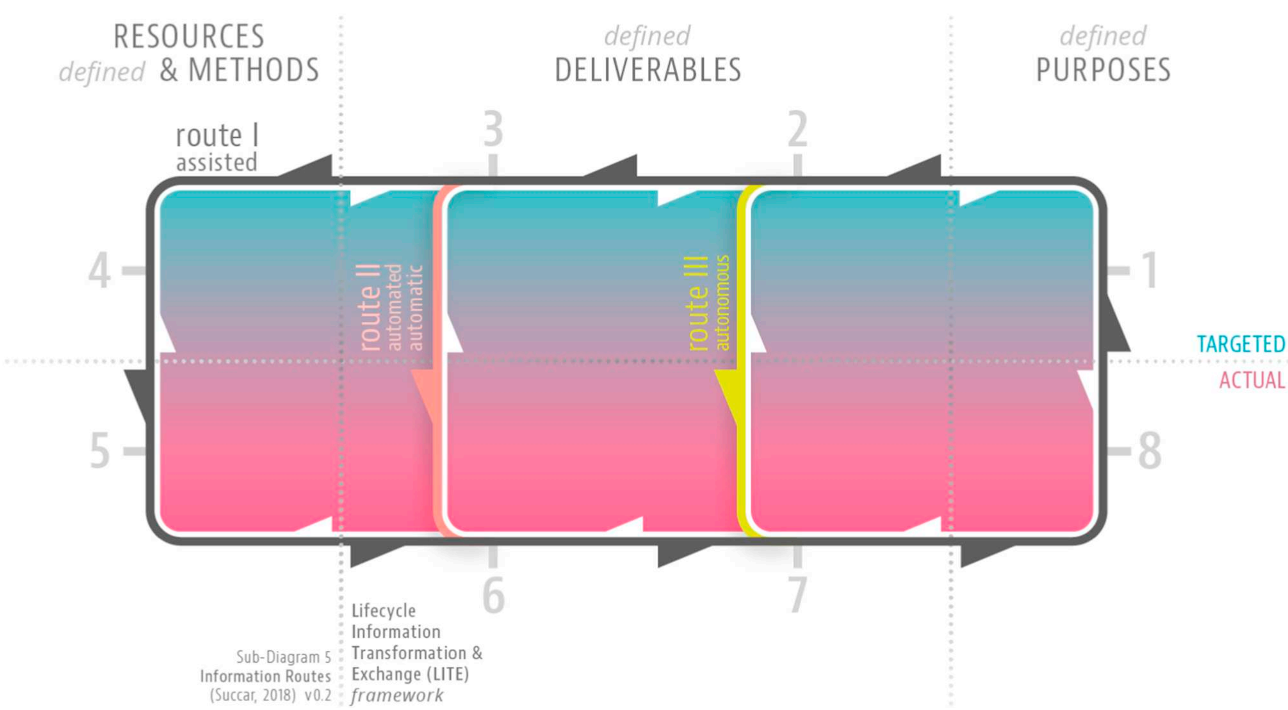

Fig. 7. LITE framework – *Information Routes* (larger image).

[116,117].

There are also two *horizontal couples*: Deliverables Couple [milestones 2 and 3] representing the need to continuously synchronise *expected* Physical Deliverables with their *targeted* Digital counterparts; and Assets Couple [milestones 6 and 7] representing the need to continuously synchronise *actual* Digital Assets with their Physical counterparts (e.g. Digital twinning).

2.4. Information Flows and Gates

Information Flow refers to the movement of information within and between Information Milestones throughout an asset's lifecycle; while Information Gates refer to the mechanisms controlling these flows. As illustrated in Fig. 6, information flows in *forward*, *reverse, inward*, and *outward* directions:

- ➔ Forward Flow (counter-clockwise) represents the primary flow of information being transformed and exchanged – where Purposes *influence the definition of* Deliverables, and Deliverables *influence the definition of* Resources and Methods needed to deliver them. Clusters of activities *flowing forward* are referred to as Execution Actions – similar to design, delivery, and utilisation;
- ➔ Reverse Flow (clockwise) represents the flow of information to check what is *actual* against what was *targeted*, and to verify physical deliverables against their digital counterparts. Clusters of activities *flowing in reverse* are referred to as Measurement Actions – similar to assessment, verification, and validation;
- ➔ Inward Flow (towards the centre) is the flow direction representing the collation of information. Clusters of activities *flowing inwards* are referred to as Capturing Actions – similar to learning and integrating data; and
- ➔ Outward Flow (away from the centre) is the flow direction representing the release of information. Clusters of activities *flowing outwards* are referred to as Sharing Actions – similar to teaching and releasing data.

Controlling these Information Flows are Information Gates – key decision points [80], financial controls, security reviews, and legal checks. In Fig. 6, gates coincide with Information Milestones controlling what information flows *through* each milestone to the next one.

Information flows are verified and validated at Information Gates by conducting numerous checks. These include checking information – in their digital or physical manifestations - for their accuracy, timeliness, completeness, and – most importantly – alignment with Defined Purposes. Depending on the Information Route followed (refer to "Information Routes"), checks may be automated, automatic, or autonomous. Also, analogous to flow gates on a water causeway, Information Gates may slow, restrict, or divert the flow of information along different routes and/or to varying Information Actors depending on their roles and permission levels (note: information *flow dynamics* will be discussed in a future publication).

2.5. Information Routes

There are three Information Routes (Fig. 7) that information can follow once they Enter into the Information Loop (refer to "Information Loops"). The route to follow depends on the type of asset being delivered, the actors – humans and/or machines – involved in the delivery, and the checking mechanisms within Information Gates:

Route I: Assisted Flow
: Route I is the longest route and includes all eight Information Milestones. This *machine-assisted* information route is travelled when (a) the resources – the personnel, equipment, and/or methods - necessary to deliver the Digital or Physical Assets are not known at the start of the Information Cycle, or where (b) automation is neither available, efficient nor desirable (e.g. where manual checks provide more insights or better value). If the Information Cycle repeats to deliver similar assets (refer to Full Information Loop) and uses the same resources/methods, then a shorter route can be followed.

Route II: Automated and Automatic Flows
: Route II is shorter than Route I due to the gains made from partial or full automation of information exchanges. Automated (instigated by an actor) and Automatic (instigated by a trigger event) Information Flows exist in many forms [118–123]. Automated and Automatic flows represent a valid route to follow when (a) the activities that need to be performed are well-defined; (b) the Needed Resources and Methods to execute these activities are *pre-defined* and are available for use; (c) automation tools are available; and (d) there are enough incentives to automate a full process, an activity, or a single task. Traversing this route allows information to bypass Information Milestones [4] and [5] within the Information Cycle.

Route III: Autonomous Flow
: Route III is the shortest route to account for the autonomous *delivery* of Physical Assets – through swarm robotics [124–126], generative design [127–129], and Artificial Intelligence [19,20]. This delivery follows the definition of their geometric/spatial attributes and/or their expected functional performance. Traversing this route, Information Flows bypass Information Milestones [3–6], and enable significant efficiencies – not only by optimising Digital Assets according to Defined Purposes but – by optimising the construction, inspection, and operation of Physical Assets [130–132].

The three Information Routes are not mutually exclusive, and the delivery/utilisation of Digital and Physical Assets may include concurrent activities, each conducted at a measurable Degree of Autonomy (DoA):

- ➔ [0] Manual: the activity is manually executed by a human actor *without any assistance* from a machine actor. These manual activities are not illustrated in the LITE framework (Fig. 2) as it focuses exclusively on structured, computable information;
- ➔ [1] Assisted: the activity or task is manually executed by a human actor *with the assistance* of a machine actor (e.g. computer draughting or site excavation using dedicated software/hardware tools);
- ➔ [2] Automated: the activity or task is executed by a machine actor upon initiation by a human actor (e.g. running a script to 3D-print an asset);
- ➔ [3] Automatic: the activity or task – or a cascade of activities and tasks – are executed by a machine actor following a pre-programmed initiation/actuation event (e.g. the automatic closing of all fire doors, and the sending of alarm messages to the fire brigade upon triggering of the fire-protection system); and
- ➔ [4] Autonomous: the activity or task – or a cascade of activities and tasks – are executed by a machine actor based on a variety of decision heuristics and/or sensor data. These decisions are taken independently by the machine actor without human intervention and are based on Artificial Intelligence and – more specifically - Machine Learning and Deep Learning [133].

The Degree of Autonomy reflects many factors including the availability of automation resources, the competency of human information actors, and the nature of the Information Activity itself. Automation of activities may increase the Level of Accuracy but may also decrease the Level of Detail (geometric and semantic) [134,135]. The Degree of

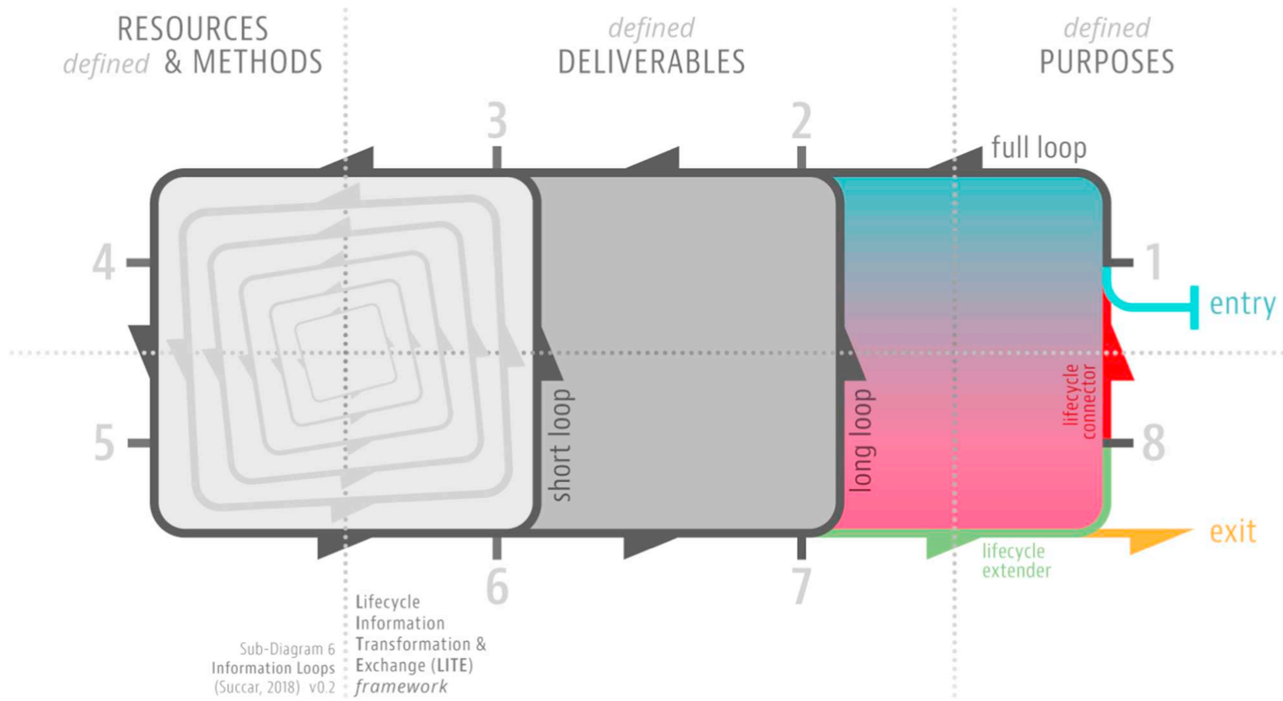

Fig. 8. LITE framework – *Information Loops* (larger image).

Autonomy index – in its current development form - is descriptive, intended to highlight flow variations within an Information Cycle. The index however is not intended to identify what activities *can* be automated, *need* to be automated, and to what automation degree. For such decisions, the LITE framework relies on more specialised automation (computerisation and mechanisation) indices developed in the fields of human-machine-interaction, robotics, and artificial intelligence [136–138].

Without attempting to foresee the future development of technology [139,140], the LITE framework accounts for the gradual and inevitable progression towards automation, autonomy, and the minimisation of manual input. Also, by including multiple routes, it allows for any potential combination of *serial*, *parallel* and *coupled* information flows across the design, delivery, and utilisation phases of assets [178]. Finally, while offering concurrent paths for information *exchange* and enabling varied degrees of autonomy, the three Information Routes equally enable the *transformation* of information from their *targeted* Status to their *actual* one, and from their *digital* representation to their *physical* one.

2.6. Information Loops

The routes discussed earlier - assisted, automated, and autonomous – form *open* or *closed* Information Loops. Open loops are when information flows *once* along a route, while closed loops are when – some or all – information flows two or more times along a route. Fig. 8 identifies three Information Loops – Full, Short, and Long:

➔ A Full Information Loop spans the entirety of an Information Cycle - starting *from* and *back to* Information Milestone 1. When the Full loop is *open*, some/all information may Exit from the Information Loop (shown as an orange arrow at the bottom-right of the image). Information exits due to (i) inadvertent *Information Loss*; (ii) *Information Archiving* for future reuse, reference, or as a regulatory audit-trail; or (iii) *Information Purging* (deleting redundant or duplicate info). When *closed* through the Lifecycle Extender (shown in green between milestones 7 and 8) and the Lifecycle Connector (connecting the end of one cycle to the start of another – shown in red between milestones 8 and 1), the information continues to flow to the next Information Cycle. The extender and the connector prolong the utilisation of information from Cradle-to-Grave to Cradle-to-Cradle thus allowing asset refurbishment, recycling, and reuse [141,142] and – at a macro scale – support the tenets of a more efficient Circular Economy [143–145];

➔ A Short Information Loop connects Actual Digital Assets [Information Milestone 6] back with Targeted Digital Deliverables [Milestone 3]. When information loops back from 6 to 3, it indicates a Design Iteration (versioning): a partial or complete re-design of an asset, or a variation in a Digital Asset's Levels of X[2]. If the same Resources and Methods are used, or if the iteration is conducted in an automated/automatic fashion, then Milestones 4 and/or 5 may be bypassed (refer to "Information Shortcuts"); and

➔ A Long Information Loop connecting Actual Physical Assets [Information Milestone 7] back with Expected Physical Deliverables [Milestone 2]. When information loops back from 7 to 2, it indicates a Delivery Iteration: a re-construction, re-manufacturing, customisation, and/or a correction of a design, construction, fabrication, or installation error. Similarly, if the iteration is partially or fully conducted in an automated/automatic or autonomous fashion, then Milestones 4 and/or 5 may be bypassed.

In the LITE framework, an asset can be of any Asset Scale [115]: a single component (e.g. hydraulic pump), a system (e.g. water recycling system), or a whole facility (e.g. the municipal water utility buildings). Each asset may have its own information lifecycle or is included in the information lifecycle of its parent asset. Whether an asset – of any Asset Scale - is designed/delivered in a single or multiple iterations, the three loops – when adopting an Agile/Scrum language – constitute Information Sprints of varied durations [146–149]. In combination, these

[2] Level of X is a generic term referring to all varieties of modelling specifications similar to Level of Development, Level of Definition, Level of Detail, Level of Information Need, and Level of Accuracy. Level of X (LoX) is not a real index but a collective reference to all current and future variations of the above.

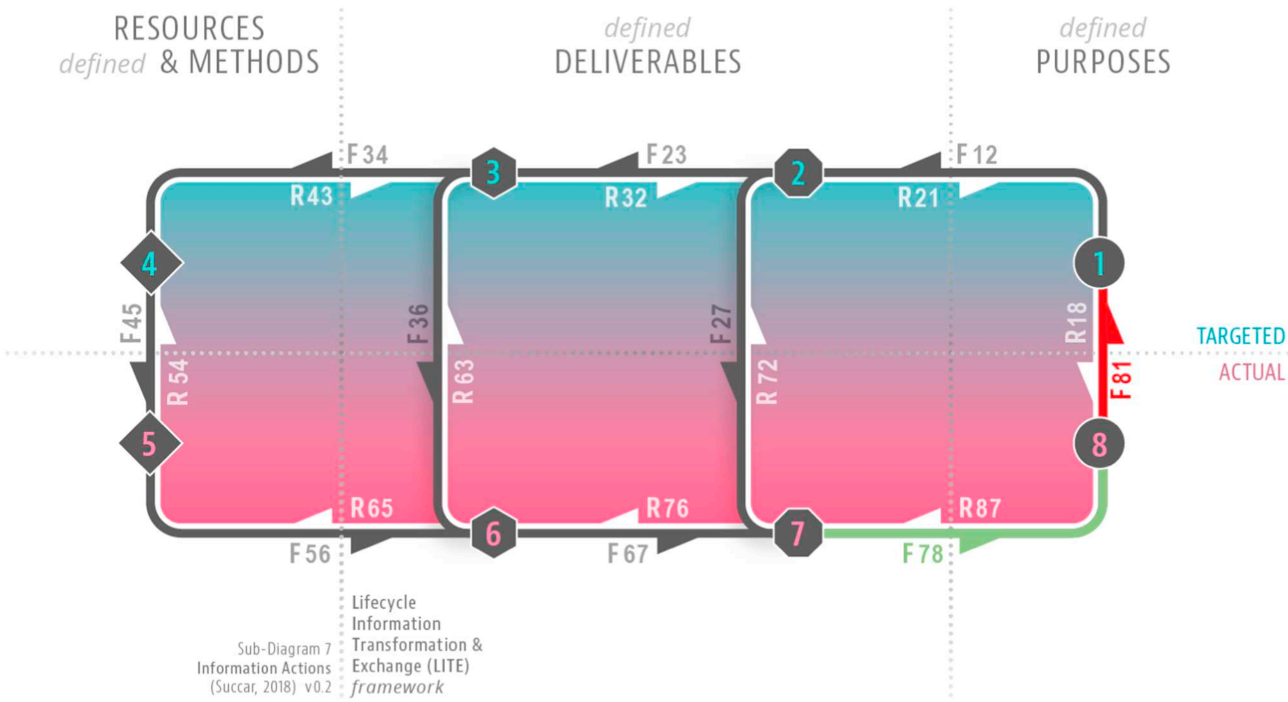

Fig. 9. LITE framework – *Information Actions* (larger image).

Table 2
Information Actions.

From	Towards	Forward *Execution Actions*	Reverse *Measurement Actions*
[1] Intent to deliver new assets	[2] Expected physical deliverables	F1–2 | Specify the physical and functional properties of the Assets to be delivered by the Supply Entity	R2–1 | Confirm that the Expected Physical Assets – as defined - meet the Purposes set by the Demand Entity
[2] Expected physical deliverables	[3] Targeted digital deliverables	F2–3 | Define the Digital Deliverables *needed* for the design, delivery, and/or utilisation of the Expected Physical Deliverables	R3–2 | Verify that the defined Digital Deliverables are adequate for designing, delivering, and/or utilising the Expected Physical Deliverables
[3] Targeted digital deliverables	[4] Needed resources and methods	F3–4 | Identify the Resources and Methods *needed* to generate the Targeted Digital Deliverables and deliver the Expected Physical Assets. This action includes deconstructing targeted deliverables into allocate-able activities and tasks, and the generation of a *responsibility matrix* [80] ([150], Item 3.16) or similar	R4–3 | Analyse if the identified resources and methods are adequate for the generation of expected Digital Deliverables and the delivery of *expected* Physical Deliverables. Also, to reduce waste, analyse resource availability/constraints against work availability/ constraints
[4] Needed resources and methods	[5] Available resources and methods	F4–5 | Assign resources and deploy methods to deliver Targeted Digital Assets and Expected Physical Assets	R5–4 | Assess *actual/available* Resources and chosen Methods against *needed* resources and methods
[5] Available resources and methods	[6] Actual digital assets	F5–6 | Generate the Digital Assets using the *available* Resources and chosen Methods	R6–5 | Evaluate if the deployed Resources and Methods were adequately utilised in generating the Actual Digital Deliverables
[6] Actual digital assets	[7] Actual physical assets	F6–7 | Deliver the Physical Assets as per corresponding Digital Deliverables	R7–6 | Check the delivered Physical Assets against their digital counterparts
[7] Actual physical assets	[8] Intent to reuse existing assets	F7–8 | Operate the Physical Assets, and maintain each according to expectations set by the Demand Entity *Note: **F7–8** is the Lifecycle Extender (extending Project Lifecycle into Asset Lifecycle)*	R8–7 | Inspect if the operation and maintenance activities are conducted according to the defined *expectations* of the Demand Entity
[8] Intent to reuse existing assets	[1] Intent to deliver new assets	F8–1 | Renovate, extend, and/or reuse the assets *Note: **F81** is the Lifecycle Connector (connecting one Information Cycle to another)*	R1–8 | Evaluate if existing assets can be refurbished, recycled, or reused instead of generating new assets
Route II: Automated Flow [3] Targeted Digital Deliverables *Not to be confused with Information Shortcut* S3-6 *in the next subsection*	[6] Actual digital deliverables	F3–6 | Generate - in an automated or automatic process – the Actual Digital Assets according to Targeted Digital Deliverables	R6–3 | Validate - in a computer-assisted, automated, or automatic process - Actual Digital Assets against Expected Digital Deliverables. Also measure the digital health, quality, and compliance of deliverables against applicable codes and protocols
Route III: Autonomous Flow [2] Expected Physical Deliverables *Not to be confused with Information Shortcut* S2–7 *in the next subsection*	[7] Actual physical assets	F2–7 | Deliver - in an autonomous fashion – the Actual Physical Assets according to Expected Physical Deliverables	R7–2 | Verify - in a computer-assisted, automated, automatic, or autonomous process – the Actual Physical Assets against Expected Physical Assets

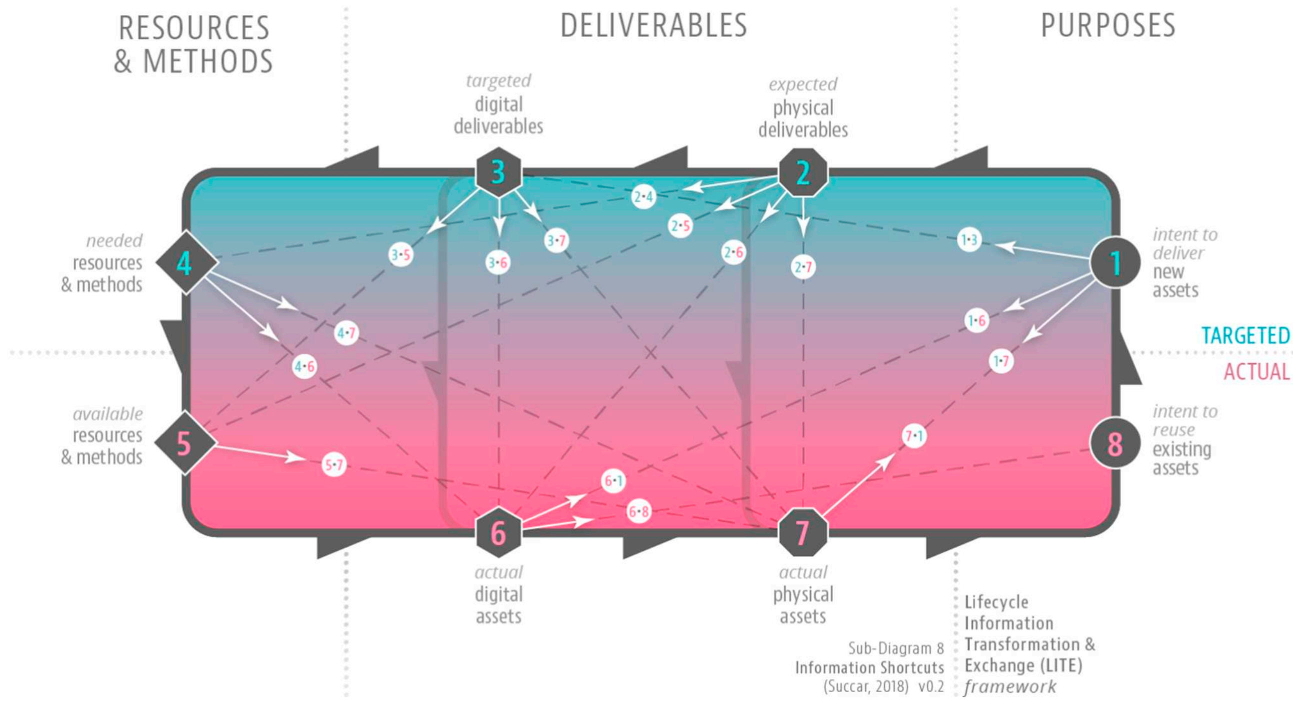

Fig. 10. LITE framework – *Information Shortcuts* (larger image).

Table 3a
Information Shortcuts – milestones bypassed

	Information Shortcut From/To	Milestones bypassed if an Information Shortcut is taken
S1_3	From [1] Intent to Deliver New Assets to [3] Targeted Digital Deliverables	[2] Expected Physical Deliverables
S1_6	From [1] Intent to Deliver New Assets to [6] Actual Digital Assets	[2] Expected Physical Deliverables, [3] Targeted Digital Deliverables, [4] Needed Resources and Methods, and [5] Available Resources and Methods
S1_7	From [1] Intent to Deliver New Assets to [7] Actual Physical Assets	[2] Expected Physical Deliverables, [3] Targeted Digital Deliverables, [4] Needed Resources and Methods, [5] Available Resources and Methods, and [6] Actual Digital Assets
S2_4	From [2] Expected Physical Deliverables to [4] Needed Resources and Methods	[3] Targeted Digital Deliverables
S2_5	From [2] Expected Physical Deliverables to [5] Available Resources and Methods	[3] Targeted Digital Deliverables, and [4] Needed Resources and Methods
S2_6	From [2] Expected Physical Deliverables to [6] Actual Digital Assets	[3] Targeted Digital Deliverables, [4] Needed Resources and Methods, and [5] Available Resources and Methods
S2_7	From [2] Expected Physical Deliverables to [7] Actual Physical Assets *Not to be confused with Information Route III*	[3] Targeted Digital Deliverables, [4] Needed Resources and Methods, [5] Available Resources and Methods, and [6] Actual Digital Assets
S3_5	From [3] Targeted Digital Deliverables to [5] Available Resources and Methods	[4] Needed Resources and Methods
S3_6	From [3] Targeted Digital Deliverables to [6] Actual Digital Assets *Not to be confused with Information Route II*	[4] Needed Resources and Methods, and [5] Available Resources and Methods
S3_7	From [3] Targeted Digital Deliverables to [7] Actual Physical Assets	[4] Needed Resources and Methods, [5] Available Resources and Methods, and [6] Actual Digital Assets
S4_6	From [4] Needed Resources and Methods to [6] Actual Digital Assets	[5] Available Resources and Methods
S4_7	From [4] Needed Resources and Methods to [7] Actual Physical Assets	[5] Available Resources and Methods, and [6] Actual Digital Assets
S5_7	From [5] Available Resources and Methods to [7] Actual Physical Assets	[6] Actual Digital Assets
S6_1	From [6] Actual Digital Assets to [1] Intent to Deliver New Assets	[7] Actual Physical Assets, and [8] Intent to Reuse Existing Assets
S6_8	From [6] Actual Digital Assets to [8] Intent to Reuse Existing Assets	[7] Actual Physical Assets
S7_1	From [7] Actual Physical Assets to [1] Intent to Deliver New Assets	[8] Intent to Reuse Existing Assets

loops/sprints allow for the use, reuse, and planning for reuse of information in subsequent activities, stages/phases, projects, and asset lifecycles [141,143].

2.7. Information Actions

Information Actions are clusters of granular information activities and tasks. Fig. 9 illustrates two of these actions as *Forward* (F) Execution and

Table 3b
Information Shortcuts – valid bypass reason and potential bypass risks

Milestones bypassed	Valid bypass reason	Potential bypass risks
[1] Intent to Deliver New Assets *Bypass not shown in image*	Shortcut is valid if no new assets are targeted for design or delivery within the current Information Cycle or Loop	Risk of defining assets without first defining the *functions needed* and *value sought* from these assets
[2] Expected Physical Deliverables	Shortcut is valid if no Physical Assets are targeted for design or delivery within the current Information Cycle or Loop	Risk of delivering Physical Assets that *do not match* the Demand Entity's original intent
[3] Targeted Digital Deliverables	Shortcut is valid if no Digital Assets are targeted for design or delivery within the current Information Cycle or Loop	Risk of delivering Digital Assets that *do not match* the Demand Entity's original intent or enable the delivery of Expected Physical Assets (if defined)
[4] Needed Resources and Methods	Shortcut is valid if Route II or III are followed or if existing Resources and Methods are the only ones available during the current Information Cycle or Loop	Risk of utilising *inadequate resources* – incompetent human or ineffective machine actors - and deploying *nonoptimal methods* for delivering the Targeted Digital Assets or Expected Physical Assets (if defined)
[5] Available Resources and Methods	Shortcut is valid if Route II or III are followed	Risk of *not receiving* any or some of the Targeted Digital Assets or Expected Physical Assets (if defined)
[6] Actual Digital Assets	Shortcut is valid if Route III is followed; if the Physical Assets are simple and would not benefit from a digital mock-up; or if the new Physical Assets are a direct replication of existing/available ones	Risk of delivering Physical Assets without being digitally tested/ analysed and without having a digital record to use/reuse
[7] Actual Physical Assets	Shortcut is valid if no Physical Assets are needed during the current Information Cycle or Loop	Risk of not actualising the Physical Assets (if Expected Physical Assets were defined)
[8] Intent to Reuse Existing Assets	Shortcut is valid if the existing assets cannot be reused	Risk of not checking whether existing assets can or should be reused (if reuse was defined in the Expected Physical Assets)

Reverse (R) Measurement connections between Information Milestones (refer to "Information Flows and Gates"). For example, F1-2 is a Forward action from milestone 1 to 2, and R2-1 a Reverse action from milestone 2 back to 1. Table 2 identifies these actions along the three Information Routes:

Information Actions represent clusters of Activities that can be further subdivided into sub-Activities, Tasks, sub-Tasks, and Steps (smallest increment). Each of these subdivisions may require its own Resources and Methods which – if not pre-defined in previous Information Cycles/Loops - need to be defined in the current Information Cycle/Loop.

2.8. Information Shortcuts

Information Shortcuts are information flows that bypass one or more Information Milestones. Shortcuts either have a valid reason or represent a potential risk, a divergence from the three routes. This divergence may cause a decrease in information clarity, an increase in waste, and may indicate willful avoidance of checking mechanisms (Information Gates).

The framework identifies multiple shortcuts (Fig. 10) bypassing one or more Information Milestones. A bypass occurs when an Information State – a purpose, deliverable, or resource/method – is not '*defined*' and thus remains unavailable for execution or measurement. Table 3a identifies sixteen Information Shortcuts and their respective Milestones Bypassed. Each bypass may have a Valid Bypass Reason and/or a Potential Bypass Risk (Table 3b). Since shortcuts may bypass more than one milestone, the risks – if there are no valid reasons (e.g. availability of an automated/automatic or autonomous option) – will compile and increase. For added clarity, if Information Milestone 2 is bypassed (e.g. in **S1–3**), this bypass may be for a valid reason [Valid Reason 2] or may pose a potential risk [Potential Risk 2].

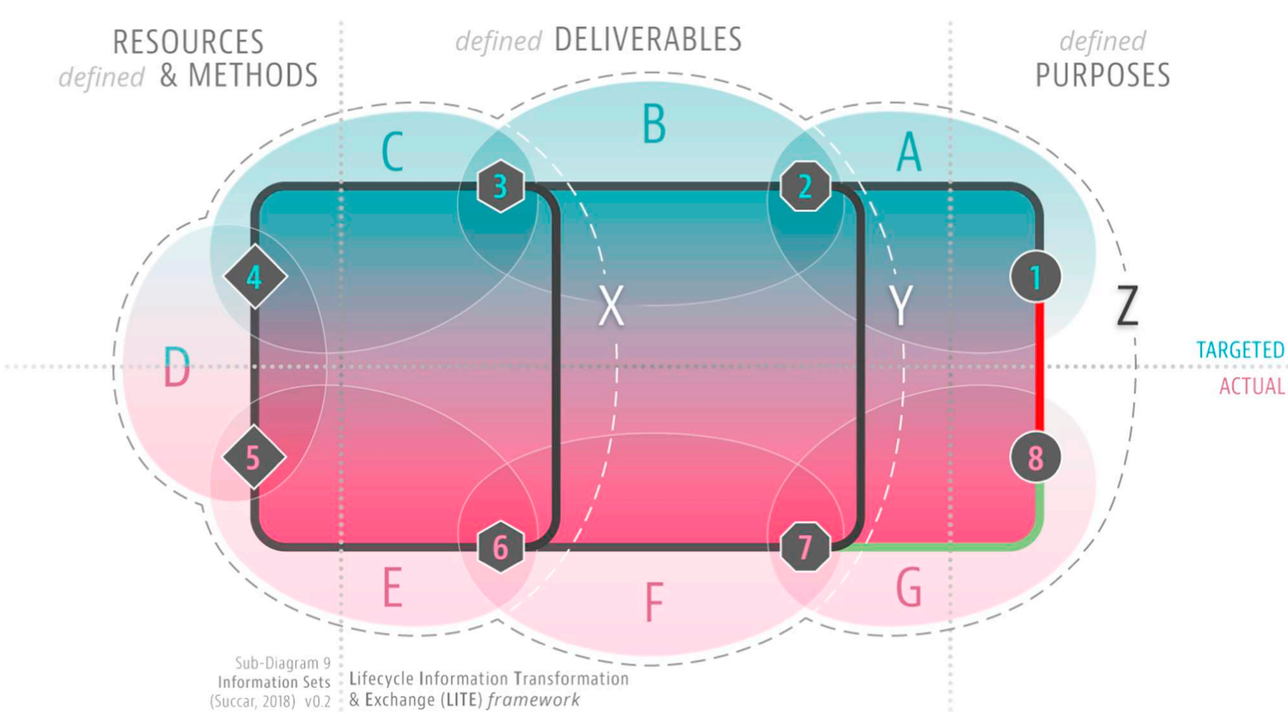

Fig. 11. LITE framework – *Information Sets* (larger image).

Table 4
Information sets – focus on specifications.

Information sets (to be progressively populated, updated, or purged)	Information milestones (covered by each set)	Specifications (SP) to be captured (at each milestone)
Information Set A defines the assets *to be* delivered upon completion of an Information Cycle	*From* [1] Intent to Deliver New Assets *to* [2] Expected Physical Deliverables	SP1 Physical Asset Specifications cover the location, form, function, cost, use, operation, maintenance, and reuse of the Expected Physical Assets
Information Set B defines the information *to be* generated in digital format to represent, simulate, quantify, and qualify the Expected Physical Deliverables	*From* [2] Expected Physical Deliverables *to* [3] Targeted Digital Assets	SP2 **Digital Asset Specifications** cover the Targeted Digital Assets - the Model Uses, Document Uses, and Data Uses - to be generated, exchanged, and delivered. SP2 may also include detailed exchange requirements defined by the Demand Entity
Information Set C defines the resources, abilities, and methods *needed* to deliver the Digital Assets and/or Physical Assets	*From* [3] Targeted Digital Assets *to* [4] Needed Resources and Methods	SP3 **Resources and Methods Specifications** cover the equipment, digital solutions, methods, and abilities (competence of individuals/groups, capability/maturity of organisations, and compatibility of work/project teams) needed to deliver the Expected Physical Assets
Information Set D identifies *available* resources, abilities, and selected delivery methods	*From* [4] Needed Resources and Methods *to* [5] Available Resources and Methods	SP4 ***Updated* Resources and Methods Specifications** is a post-vetting or post-tender (contract award) update of the specifications within Set C. SP4 includes the vetting criteria for future analysis and comparison of expected performance against actual performance
Information Set E clarifies how and when, and whom will generate the Digital Assets for design, delivery, and utilisation of Physical Assets	*From* [5] Available Resources and Methods *to* [6] Actual Digital Assets	SP5 **Digital Delivery Specifications** cover the tools, workflows, and protocols to be used by the Supply Entity to deliver the Digital Assets and satisfy the exchange requirements of the Demand Entity
Information Set F clarifies how to deliver the Physical Assets according to what was defined in the Digital Assets	*From* [6] Actual Digital Assets *to* [7] Actual Physical Assets	SP6 **Physical Delivery Specifications** cover the instructions to be followed to procure, construct, manufacture, and/or assemble the Physical Assets
Information Set G clarifies how to operate, manage, maintain, and reuse existing assets	*From* [7] Actual Physical Assets *to* [8] Intent to Reuse Existing Assets	SP7 Asset **Utilisation Specifications** cover the utilisation, management, maintenance, and decommissioning, and reuse of Digital and Physical Assets
Information Set X identifies the information generated or modified during Design Iterations (Short Information Loop)	*From* [3] Targeted Digital Assets *to* [6] Actual Digital Assets	No new specifications generated; SP3-SP5 are updated to capture modifications to Digital Assets
Information Set Y identifies the information generated or modified during Delivery Iterations (Long Information Loop)	*From* [2] Expected Physical Deliverables *to* [7] Actual Physical Assets	No new specifications generated; SP2-SP6 are updated to capture modifications to Digital and Physical Assets
Information Set Z identifies the information to be carried forward from one Information Cycle to another	*From* [8] Intent to Reuse Existing Assets *to* [1] Intent to Deliver New Assets	No new specifications generated; the Information Pool (SP1-SP7) is updated to enable recycling and/or reuse of Digital and Physical Assets

2.9. Information Sets

Information Sets collect information covering *what and why* assets need to be delivered, and *how, when, and by whom* they need to be acted upon. Sets collectively cover all 'To Be' and 'As Is' information as it gets transformed/exchanged between information Statuses and States.

Integrating information across a project or asset's lifecycle is dependent on, first, having all information clearly *defined* and, second, on successfully *managing* this information. Once managed properly by a human or machine actor, integration of information across systems and assets becomes possible. In contrast, without clear definition and proper management of various types of information, there is no possibility to progressively integrate asset lifecycle information into a *unified* Information Pool (e.g. an online database) for all stakeholders to *contribute to* and *benefit from*.

To enable such a unified Information Pool, the framework collates lifecycle information through consecutive and overlapping Information Sets, each connecting two or more Information Milestones. The population of the *first* Information Set A is initiated once there is an *Intent to Deliver a New Asset* (Information Milestone 1). Following that, Information Sets are progressively *populated* (information added), *updated* (information replaced), and *purged* (redundant information removed) throughout the Information Cycle.

As illustrated in Fig. 11, there are ten *Information Sets* (A-G and X-Z) connecting the eight *Information Milestones* [1–8]. These sets collect information from *Beginning of Life* (BoL), through *Middle of Life* (MoL), and to the asset's *End of Life* (EoL) [151,152]. The information collected through Information Sets can either be *integrated* with other information, *collated* without integration, or merely *referenced* (refer to "Information Tiers").

2.9.1. Types of information captured

Information is *collated* through three types of documents/modules: Specifications, Protocols, and Plans [153,154]:

- ➔ Specifications (SP) collate and define WHAT outputs (products or services) are targeted for delivery; WHAT capabilities/competencies are needed to deliver these outputs; and WHY these specific outputs are targeted (the intention behind or value sought from the output – e.g. to satisfy Organisation-, Project-, and/or Market-specific Purposes). Specifications are the core around-which lifecycle information is captured. Examples include *Physical Asset Specifications* and *Asset Utilisation Specifications* which are developed at the start (Entry into the Information Loop) and conclusion (Exit from the Information Loop) of an asset information lifecycle. Specifications rely on numerous templates (forms in an online platform) to organise the capture of pertinent information in a structured and repetitive manner. Once populated, templates are transformed into information sheets, reports, records, and similar. For example, a *Product Information Template* captures pertinent information about 'products' – e.g. their physical properties, performance parameters, and maintenance requirements - and are then used to generate multiple *Product Information Sheets*;
- ➔ Protocols (PR) collate and prescribe HOW an output needs be delivered: the activities to be completed and the standards to be followed. Protocols are applicable across Project Lifecycle Phases - Design [D], Construction [C], Operation [O], and their overlaps [DC], [DO], [CO], and [DCO] [155]. Each Protocol includes provisions (sub-protocols) for *Information Security*, *Information Quality*, and *Information Privacy* which may vary by *Asset Scale* (e.g. a single hydraulic pump or a whole sewage treatment facility), *Asset Function* (e.g. prisons will have different security provisions than those of

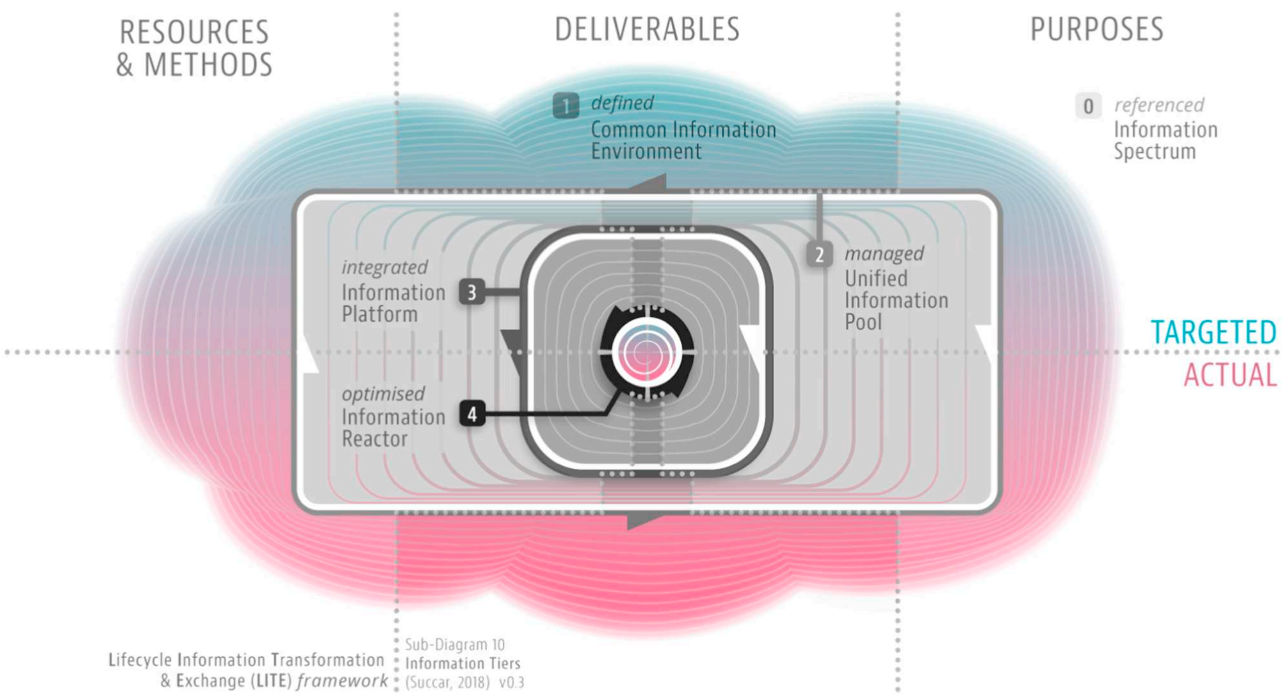

Fig. 12. LITE framework – *Information Tiers* (larger image).

residential buildings) and by *country/jurisdiction*. Examples include the *Information Request Protocol* and the *Information Storage and Disposal Protocol*; and

➔ Plans (PL) collate and clarify the WHEN, WHERE, at what COST, and BY WHOM the outputs need to be delivered. Examples include *Community Engagement Plan* and *Crane Lifting Plan*.

Table 4 identifies the Information Sets to be populated throughout the Information Cycle:

Information Sets enable the early collation and paced integration of asset lifecycle information into a unified Information Pool. Initially populated with essential information about the Expected Physical Asset, the pool is progressively enriched with more detailed, or more accurate product and process information. The early capture of asset information addresses a key industry concern that "most current asset management practice relies [on] retrospective asset information collected and interpreted after design and construction" ([156], p. 4).

2.9.2. Information flow across sets

As a sample Information Flow, Information Set A identifies the physical assets (e.g. an Elevator System) to be managed and tracked throughout a facility's lifecycle - including the assets' function and nominal properties. Set B identifies the digital assets that need to be delivered at the end of the design/selection process. Set C identifies the competency profile of the actors to deliver the digital and physical assets (e.g. a design engineer and/or the asset's vendor) and methods to be deployed to deliver both the digital and physical Assets. Set D identifies the actual actor(s) commissioned with designing and delivering the asset. Set E captures the processes, decisions, and selections made by the actor(s) leading to the delivery of the digital assets. Set F captures the actual (what, who, how, where, and when) activities conducted, and the actual selections made leading to the delivery of the physical assets – including actual supplier, installation date, installation method, serial number, warranty date, and maintenance regime for the assets and their dependent assets. Set G captures all utilisation information covering the assets including – for a sample physical asset – commissioning, maintenance, decommissioning, and reuse. Sets X, Y, and Z capture all modifications made to the assets during their journey from *Beginning of Life* (BoL), through *Middle of Life* (MoL), to their respective *End of Life* (EoL) [151,152].

2.9.3. Information capture into sets

Information capturing into complementary sets expands upon what is detailed within international standards and protocols – e.g. the Construction Operation Building information exchange (COBie) 'standard' (NBIMS, 2015) - by facilitating the collation and subsequent integration of all Needed Information across an asset's lifecycle. Sets can include all information covering both physical and digital assets in their respective targeted and actual states, not just information covering maintainable physical assets. Capturing such information where needed allows the generation of an *audit trail,* a threaded history of a single product or a whole system for the purposes of reducing risk, monitoring health and safety, ensuring regulatory compliance, and increasing transparency.

To collate and integrate information into Information Sets, the framework deploys a process-oriented language to deliver Activity Flow Diagrams[3] informed by applicable standards [86,157,158] at multiple Granularity Levels [159].

2.10. Information tiers

Throughout the lifecycle of an asset, not all information available are *needed*; not all needed information can be *captured*; and not all captured information can be *integrated.* As detailed in previous published research [91,160], for a concept or system (e.g. an Information Management System) to be considered *Integrated* (Maturity Level d), it needs to be first properly *Defined* (Level b), *Managed* by a competent actor (Level c), and then eventually *Integrated* (Level d) with other managed systems (e.g. with the Knowledge Management System and Learning Management System). The highest maturity – *Optimised* (Level e) – signals the continual improvement of integrated systems.

[3] Please refer to https://bimexcellence.org/projects/integrated-information-platform/model-use-templates/

2.10.1. Degree of Integration

As illustrated in Fig. 12, the framework identifies five Information Tiers reflecting a Degree of Integration (DoI) index for referencing, defining, managing, integrating, and continuously optimising asset lifecycle information:

➔ [0] Referenced Information that *is needed* but *is not captured*. Referenced information typically includes externally defined legal provisions, insurance policies, codes of practice, guidance frameworks, and standards to be followed in a specific market or on a specific project. For example, Information Sets may reference specific items from ISO or ANSI standards [23,161]; NEC or FIDIC contracts [162,163]; or OmniClass, UniClass, or CoClass classifications [110,164,165]. Referenced Information is part of the overall Information Spectrum which includes both *needed* and *available* information;

➔ [1] Defined Information that *is needed* and thus *captured* within the Common Information Environment (refer to Table 1). Defined information is not necessarily connected to each other but are *visible* to all actors – according to their access level - across the environment;

➔ [2] Managed Information that has been *inspected, harmonised, normalised*, and can thus be used as part of a *unified* Information Pool. Changes in one set of managed information may cause changes in other sets/subsets;

➔ [3] Integrated Information that has the same schematic structure and thus populate an *integrated* Information Platform. Integrated information can be seamlessly transformed and exchanged from one Information Status/State/Milestone to another throughout the asset's lifecycle. Any changes in a set of integrated information triggers a change to all sets/subsets; and

➔ [4] Optimised information that is continuously updated throughout the asset's lifecycle using input from interconnected networks, distributed ledgers, and centralised databases - e.g. sensory data through the Internet of Things (IoT) and open-access public databases [166,167]. Optimised information is enabled by Artificial Intelligence and interacts within the core Information Reactor that *continuously and autonomously* processes information transformations and exchanges throughout the asset's lifecycle.

By progressively organising information capture and sharing through a *defined* Common Information Environment, a *managed* Unified Information Pool, and then an *integrated* Information Platform, the LITE framework can bridge information silos and minimise reliance on discrete documentation with overlapping contents - e.g. Organisation-, Asset-, Project-, and Exchange Information Requirements [80]. This would reduce the risks, waste, and complexity inherent in duplicating information capture/sharing and would improve both information flow and interconnectedness across an asset's lifecycle.

3. Validation

3.1. Completed development and validation rounds

The development and instantiation of the LITE framework follows an extended research and development path with multiple Development and Validation Rounds. The three completed rounds are briefly summarised below:

Round 1:
The initial manuscript was prepared describing the LITE framework and explaining many of its conceptual components. The framework development followed a literature review and relied on the researchers' experience in and of the field of information management in the built environment. Some components were excluded from the manuscript to comply with word-count limitations of journal papers. As this first round was primarily a *theory building exercise*, the framework needed to be tested and conceptually refined before getting validated and implemented within work environments.

Round 2:
Fifteen international subject matter experts (peers) from both academia and industry were approached to establish their willingness to review the manuscript. The selection of experts was made based on their (i) individual and complementary conceptual knowledge and practical experience in the topics covered by the study (e.g. construction, asset operation, project/production management, information modelling/management, Lean/Agile methods, and research methodology); (ii) their knowledge-sharing profile (e.g. their published papers and public talks); and (iii) their willingness to conduct the review in a timely manner. The names and affiliations of these experts are included – with their permission - in the "Acknowledgements" subsection. Once the initial approval to review the manuscript was received - from twelve experts – a formal Review Request was sent including Manuscript Draft A and a brief set of review instructions. The experts where tasked with inspecting the manuscript and evaluating the LITE framework for relevance, accuracy, validity, and utility. Ten experts – five from industry and five from academia - completed the review within the set duration. Upon receiving the reviews, the first author developed a Review Summary collating all comments, suggestions, and responses. Manuscript Draft B was then developed incorporating all necessary corrections, content enhancements, and stylistic improvements. Both Manuscript Draft B and the Review Summary were sent back to the ten experts alongside an invitation to participate in an online semi-structured interview. Six semi-structured interviews were conducted to discuss the reviewers' comments and suggestions. Any additional comments and suggestions were then collated into the Review Summary document (a new section was added) and incorporated into Manuscript Draft C.

Round 3:
Manuscript Draft C was submitted to this journal including a link to an open digital store collating earlier drafts, expert comments, and responses to these comments.[4] The inclusion of earlier drafts, comments, and responses are intended to highlight the experts' contributions towards improving this paper, and to provide the reader with an audit/edit trail of arguments made, responses offered, and changes committed. Upon completion of the first round of review by the journal (major changes were requested, and a full resubmittal was recommended) significant modifications were made, and Manuscript Draft D and a Response to Reviewers' Comments were submitted for a second review. Upon completion of the second review (manuscript was accepted with minor modifications requested), Manuscript Draft E and an Updated Response to Reviewer's Comments were submitted for final approval and added to the digital store. Round 3 concluded with the publication of this paper.

3.2. Current and future development and validation rounds

As laid out in the "Methodology" subsection, the development and validation of the LITE framework (artefact), its conceptual components, and their instantiation within a digital platform will continue in an iterative manner. A number of rounds will therefore be needed for continuous *development, building, justification and evaluation* [44,168]. As discussed, the criteria for gradually testing the artefact, components, and platform are derived from integrating the Design Science Research cycle with the Normal Research Cycle (refer back to Fig. 1). This testing is conducted along a continuous research path: (i) each conceptual

[4] All manuscript drafts, review comments (by invited experts and journal reviewers) are available for inspection here.

component is independently tested for completeness, simplicity, understandability, and communicative power [47]; (ii) the overall framework - an artefact articulating these components and their relations - is tested for fidelity with real world phenomena, completeness, level of detail, robustness, internal consistency, form, content, and richness of knowledge representation; and (iii) the online platform - the technical product of the artefact and conceptual components - is tested for operationality, efficiency, and ease of use.

Upon implementation within organisations and on projects, both the framework and the platform will be evaluated for economic, technical, physical, social, political and contextual impacts ([47], p. 121). This evaluation can be conducted gradually as the LITE framework - representing *both* a Bounded and an Unbounded Systemic Innovation [169,170] – can be applied first within the confines of a single organisation (as a controlled environment) and then progressively across different organisations and on projects with different procurement methods and project delivery approaches.

4. Conclusion

This positioning paper is a response to the challenges faced by the Construction Industry as it undergoes its overdue digital transformation. Addressing these challenges cannot be conducted by adopting a “20th century management and individualistic mentality” ([171], p. 217) or by following a single standardised path, but by developing innovative process-oriented approaches that support current and foreseen - while accounting for future and unforeseen - technological innovations in a collaborative and open manner. The LITE framework offers such an alternative approach to investigating, managing, and predicting information flows across an asset lifecycle, a significant research challenge and an important business problem [168].

4.1. Discussion

The LITE framework includes numerous modular and interacting components. Due to its carefully minted terminology, conceptual structure, circularity, and multi-directional information flows, the framework can cater to *physical* and *digital* assets (e.g. a water pump and its digital representation), *small* and *large* assets (e.g. a single concrete column or a portfolio of bridges), and for assets within the construction, manufacturing, or geospatial domains (e.g. train station, train carriage, or rail network). This flexibility enables managing information flows at different scales, namely pertaining to a single information exchange activity or set of activities, a project stage/phase or a full project, or the whole asset lifecycle [143–145].

The LITE framework highlights the progression from defining the intent to deliver a new asset to realising the actual Physical/Digital Assets and to managing it throughout its lifecycle. In one way, this resembles how the Lean Construction method gives primacy to pull activities ([172,Fig. 10]; [10]). On the other hand, it is quite different by not focusing on the product/production system but on the information itself as it *flows across Milestones* and *transforms across Statuses and States*. Moreover, the design and delivery iterations through Information Loops are similar to the Agile software development method in its reliance on Sprints. Yet in another way, the LITE framework differs from the Agile method by incorporating the simultaneous development of both Digital and Physical Assets. Canvassing additional similarities and contrasts between the LITE framework and both the Lean and Agile methods, as well as other established or emerging process-oriented methods, is potentially useful to engage with their respective communities but would require further investigations beyond the scope of this paper.

The framework is unique in multiple ways. As one example, through charting nominal information routes and all possible deviations from these routes, the framework is well-suited to identify inefficient (e.g. information waste or lack of automation), incompetent, or even malicious (e.g. corrupt) information exchanges by analysing these deviations. As a second example, through its representation of both the *targeted* (To Be) and *actual* (As Is) information in both their *digital* and *physical* manifestations, the LITE framework is well suited to explore, describe, explain, and predict information flows across an asset's lifecycle. From a Critical Realist perspective, this interplay opens a line of inquiry into the concurrent digital/physical facets of the evolving built environment and our interactions with it. The LITE framework also allows – its structure is optimised for - continuous measurement at varying levels of detail:

- ➔ Highly detailed measurements can be conducted through reverse-flow actions connecting Information Milestones (refer to Table 2) that test information quality – e.g. completeness, accuracy, redundancy, well-formedness, and understandability of Digital Assets [173,174];
- ➔ Less detailed measurements can be conducted through a variety of indices – e.g. the Degree of Integration (applied within “Information Tiers”) and Degree of Autonomy (applied within “Information Routes”); and
- ➔ Overall (low detailed) measurements can be conducted by identifying information exchange *patterns* including (1) number of Information Loops (iterations) completed; (2) fluctuations in Information Richness (number of Information Uses targeted or actualised); and (3) variations in Asset Scale across Information Cycles.

Finally, through collating asset information into complementary sets that overlap all information milestones, the LITE framework enables the generation and maintenance of an asset *audit trail* and – based on ongoing research – the *tokenisation* of assets by “converting rights to an asset into a digital token on a blockchain” [175] thus allowing their real-time valuation and secure exchange [176,177]. These are but some examples of development and validation paths that need to be further investigated.

4.2. Conclusion and future work

The Lifecycle Information Transformation and Exchange (LITE) framework presented in this paper sets the foundations for developing an open access digital platform for defining, managing, and integrating project and asset lifecycle information. In addition to testing and validating these conceptual foundations, the ongoing research efforts will now focus on developing the community mechanisms to engage domain researchers and industry practitioners in delivering the digital platform and expanding the framework's underlying conceptual constructs. As a first step, the framework will be made more accessible to practitioners and researchers through targeted publications, video explanations, and social media posts. A collaboration call will then be publicly made to invite the participation of international peers in validating and extending the framework. Finally, the first set of digital platform modules will be developed, tested, and calibrated. These efforts have already begun and will soon offer an open-access information management solution for the community to test, adapt, and continuously improve.

Declaration of competing interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Al Hattab, F. Hamzeh, Using social network theory and simulation to compare traditional versus BIM–lean practice for design error management, Autom. Constr. 52 (2015) 59–69, https://doi.org/10.1016/j.autcon.2015.02.014.
[2] R. Tomek, S. Kalinichuk, Agile PM and BIM: a hybrid scheduling approach for a technological construction project, Procedia Engineering 123 (2015) 557–564, https://doi.org/10.1016/j.proeng.2015.10.108.
[3] C. Boton, L. Rivest, D. Forgues, J.R. Jupp, Comparison of shipbuilding and construction industries from the product structure standpoint, International Journal of Product Lifecycle Management 11 (3) (2018) 191–220, https://doi.org/10.1504/IJPLM.2018.094714.
[4] G. Briscoe, A. Dainty, Construction supply chain integration: an elusive goal? Supply chain management: an international journal 10 (4) (2005) 319–326, https://doi.org/10.1108/13598540510612794.
[5] C. Harland, N. Caldwell, P. Powell, J. Zheng, Barriers to supply chain information integration: SMEs adrift of eLands, J. Oper. Manag. 25 (6) (2007) 1234–1254, https://doi.org/10.1016/j.jom.2007.01.004.
[6] M.P. Nepal, S. Staub-French, Supporting knowledge-intensive construction management tasks in BIM, Journal of Information Technology in Construction (ITcon) 21 (2016) 13–38 Retrieved from http://www.itcon.org/2016/2.
[7] O. Gray, Investigation of the Suitability and Benefits of Scrum Management in Buildings Services M&E Consultancy (Master of Science), The University of Bath, United Kingdom, 2016.
[8] L. Koskela, R. Vrijhoef, Is the prevalent theory of construction is a hindrance for innovation, Building Research & Information 29 (3) (2001) 197–207, https://doi.org/10.1080/09613210110039266.
[9] C. Harty, Implementing innovation in construction: contexts, relative boundedness and actor-network theory, Constr. Manag. Econ. 26 (10) (2008) 1029–1041, https://doi.org/10.1080/01446190802298413.
[10] F.A. Picchi, System view of lean construction application opportunities. Paper Presented at the Annual Conference of the International Group for Lean Construction, Singapore, http://iglc.net/Papers/Details/155, (2001).
[11] S.D. Green, The missing arguments of lean construction, Constr. Manag. Econ. 17 (2) (1999) 133–137, https://doi.org/10.1080/014461999371637.
[12] H. Cardeira, Smart contracts and their applications in the construction industry, Paper Presented at the New Perspectives in Construction Law Conference, Bucharest, Romania, 2015 https://heldercardeira.com/1503P.pdf.
[13] Ž. Turk, R. Klinc, Potentials of Blockchain Technology for Construction Management, Procedia Engineering 196 (2017) 638–645, https://doi.org/10.1016/j.proeng.2017.08.052.
[14] O. Barima, Leveraging the Blockchain technology to improve construction value delivery: the opportunities, benefits and challenges, Construction Projects: Improvement Strategies, Quality Management, and Potential Challenges, Nova Publishers, New York: Kimberly Hall, 2017, p. 93 Retrieved from https://www.researchgate.net/profile/Ruben_Gonzalez_Crespo/publication/311289392_Knowledge_Management_Model_for_Project_Management_KMPMTIC/links/58828974a6fdcc6b790eec79/Knowledge-Management-Model-for-Project-Management-KM-PMTIC.pdf#page=105.
[15] V.P. Kumar, M. Balasubramanian, S.J. Raj, Robotics in construction industry, Indian J. Sci. Technol. 9 (23) (2016), https://doi.org/10.17485/ijst/2016/v9i23/95974.
[16] Ruggiero, A., Salvo, S., & Laurent, C. S. (2016). Robotics in Construction. (Bachelor Degree Project), Retrieved from https://web.wpi.edu/Pubs/E-project/Available/E-project-032316-150233/unrestricted/FinalReport.pdf
[17] J. Feringa, T. Krijnen, BIM and robotic manufacturing towards a seamless integration of modeling and manufacturing, Paper Presented at the IASS 2015 Amsterdam Symposium: Future Visions – Building Information Modeling, Amsterdam, 2015 https://www.researchgate.net/publication/309767728_BIM_and_robotic_manufacturing_Towards_a_seamless_integration_of_modeling_and_manufacturing/references.
[18] M. Bilal, L.O. Oyedele, J. Qadir, K. Munir, S.O. Ajayi, O.O. Akinade, ... M. Pasha, Big Data in the construction industry: A review of present status, opportunities, and future trends, Advanced engineering informatics 30 (3) (2016) 500–521, https://doi.org/10.1016/j.aei.2016.07.001.
[19] Z. Irani, M.M. Kamal, Intelligent systems research in the construction industry, Expert Syst. Appl. 41 (4) (2014) 934–950, https://doi.org/10.1016/j.eswa.2013.06.061.
[20] R. Kuenzel, J. Teizer, M. Mueller, A. Blickle, SmartSite: intelligent and autonomous environments, machinery, and processes to realize smart road construction projects, Autom. Constr. 71 (2016) 21–33, https://doi.org/10.1016/j.autcon.2016.03.012.
[21] B. Succar, Building information modelling framework: a research and delivery foundation for industry stakeholders, Autom. Constr. 18 (3) (2009) 357–375, https://doi.org/10.1016/j.autcon.2008.10.003.
[22] R.C. James, P.E. Anneli, E.D. John, A. Clinton, Digitalising asset management: concomitant benefits and persistent challenges, International Journal of Building Pathology and Adaptation 0 (0) (2018), https://doi.org/10.1108/IJBPA-09-2017-0036 null.
[23] ISO. (2018b). International Organization for Standardization | Home Page. Retrieved from https://www.iso.org/home.html. Last accessed, July 12, 2018.
[24] bSI, buildingSMART International | Home Page, Retrieved from, 2018. https://www.buildingsmart.org/.
[25] R.H. Allen, R.D. Sriram, The role of standards in innovation, Technol. Forecast. Soc. Chang. 64 (2–3) (2000) 171–181, https://doi.org/10.1016/S0040-1625(99)00104-3.
[26] D.-H. Shin, H. Kim, J. Hwang, Standardization revisited: a critical literature review on standards and innovation, Computer Standards & Interfaces 38 (2015) 152–157, https://doi.org/10.1016/j.csi.2014.09.002.
[27] G. Tassey, Standardization in technology-based markets, Res. Policy 29 (4–5) (2000) 587–602, https://doi.org/10.1016/S0048-7333(99)00091-8.
[28] I.J. Ramaji, A.M. Memari, Extending the current model view definition standards to support multi-storey modular building projects, Architectural Engineering and Design Management 14 (1–2) (2018) 158–176, https://doi.org/10.1080/17452007.2017.1386083.
[29] L. Koskela, An exploration towards a production theory and its application to construction, (Doctor of Technology), VTT Technical Research Centre of Finland, 2000 Retrieved from http://lib.tkk.fi/Diss/2000/isbn951385566X/.
[30] J. Meredith, Theory building through conceptual methods, Int. J. Oper. Prod. Manag. 13 (5) (1993) 3, https://doi.org/10.1108/01443579310028120.
[31] J.A. Zachman, A framework for information systems architecture, IBM Syst. J. 26 (3) (1987) 276–292, https://doi.org/10.1147/sj.382.0454.
[32] M. Lopes, R. Flavell, Project appraisal—a framework to assess non-financial aspects of projects during the project life cycle, Int. J. Proj. Manag. 16 (4) (1998) 223–233, https://doi.org/10.1016/S0263-7863(97)00055-0.
[33] Froese, T., & Staub-French, S. (2004). A unified approach to project management. In Towards a Vision for Information Technology in Civ. Eng. (pp. 1–12). ISBN: 978-0784407042. doi:https://doi.org/10.1061/9780784407042.
[34] V. Singh, N. Gu, X. Wang, A theoretical framework of a BIM-based multi-disciplinary collaboration platform, Autom. Constr. 20 (2) (2011) 134–144, https://doi.org/10.1016/j.autcon.2010.09.011.
[35] R. Sudarsan, S.J. Fenves, R.D. Sriram, F. Wang, A product information modeling framework for product lifecycle management, Comput. Aided Des. 37 (13) (2005) 1399–1411, https://doi.org/10.1016/j.cad.2005.02.010.
[36] J. Stark, Product lifecycle management, Product Lifecycle Management: 21st Century Paradigm for Product Realisation, 1 Springer International Publishing, Switzerland, 2015, pp. 1–29, , https://doi.org/10.1007/978-3-319-17440-2.
[37] X. Ma, F. Xiong, T.O. Olawumi, N. Dong, A.P.C. Chan, Conceptual framework and roadmap approach for integrating BIM into lifecycle Project Management, J. Manag. Eng. 34 (6) (2018) 05018011, , https://doi.org/10.1061/(ASCE)ME.1943-5479.0000647.
[38] H.A. Simon, The Sciences of the Artificial, 3rd ed., MIT Press, Cambridge, MA, USA, 1996.
[39] J. Iivari, A paradigmatic analysis of information systems as a design science, Scandinavian J. Inf. Systems 19 (2) (2007) 5 doi: Retrieved from https://aisel.aisnet.org/sjis/vol19/iss2/5/.
[40] G.M. Winch, Managing Construction Projects, John Wiley & Sons, 2009.
[41] R.H. Von Alan, S.T. March, J. Park, S. Ram, Design science in information systems research, MIS Q. 28 (1) (2004) 75–105, https://doi.org/10.2307/25148625.
[42] S.T. March, G.F. Smith, Design and natural science research on information technology, Decis. Support. Syst. 15 (4) (1995) 251–266, https://doi.org/10.1016/0167-9236(94)00041-2.
[43] J.E. Van Aken, Management research as a design science: articulating the research products of mode 2 knowledge production in management, Br. J. Manag. 16 (1) (2005) 19–36, https://doi.org/10.1111/j.1467-8551.2005.00437.x.
[44] A. Hevner, S.T. March, J. Park, S. Ram, Design science research in information systems, MIS Q. 28 (1) (2004) 75–105, https://doi.org/10.2307/25148625.
[45] B. Succar, M. Kassem, Macro-BIM adoption: Conceptual structures, Autom. Constr. 57 (2015) 64–79, https://doi.org/10.1016/j.autcon.2015.04.018.
[46] N. Cross, Design as a discipline, Designerly Ways of Knowing, 2006 978-1846283017, pp. 95–103 Retrieved from https://www.springer.com/gp/book/9781846283000.
[47] P. Järvinen, On Research Methods, Opinpajan Kirja, Tampere, Finland, 2004.
[48] R.S. Michalski, R.E. Stepp, Clustering, in: S.S. Shapiro (Ed.), Encyclopedia of Artificial Intelligence, 1 Wiley, New York, 1987, pp. 103–111 Retrieved from https://dl.acm.org/citation.cfm?id=531550.
[49] K. Van der Heijden, C. Eden, The theory and praxis of reflective learning in strategy making, in: C. Eden, J.-C. Spender (Eds.), Managerial and Organizational Cognition: Theory, Methods and Research, Sage, London, 1998, pp. 58–75 Retrieved from https://strathprints.strath.ac.uk/id/eprint/43723.
[50] D.H.T. Walker, L.M. Bourne, A. Shelley, Influence, stakeholder mapping and visualization, Constr. Manag. Econ. 26 (6) (2008) 645–658, https://doi.org/10.1080/01446190701882390.
[51] A. Sayer, Method in Social Science: A Realist Approach, Retrieved from http://bit.ly/gHz6Mddoi:, (1992) Retrieved from http://bit.ly/gHz6Md.
[52] N.W.H. Blaikie, Designing Social Research: The Logic of Anticipation, Polity Press, 2000.
[53] D. Atkinson, Approaches and Strategies of Social Research, Essay for Reasearch Methods Class, RMIT, 2011 Retrieved from http://minyos.its.rmit.edu.au/~dwa/

Methods.html.
[54] Bryant, A., & Charmaz, K. (2007). The Sage Handbook of Grounded Theory: Sage, United Kingdom. ISBN: 978-1446275728.
[55] J.R. Josephson, S.G. Josephson, Abductive Inference: Computation, Philosophy, Technology, Cambridge University Press, 1996.
[56] B. Leca, P. Naccache, A critical realist approach to institutional entrepreneurship, Organization 13 (5) (2006) 627–651, https://doi.org/10.1177/1350508406067007.
[57] S.A. Carlsson, Critical realism: A way forward in IS research, Paper Presented at the 11th ECIS 2003, Naples, Italy, 16–21 June 2003, 2003 https://dblp1.uni-trier.de/db/conf/ecis/ecis2003.html.
[58] J.A. Maxwell, A Realist Approach for Qualitative Research, George Mason University, VA: Sage Publishing, United States, 2012.
[59] G. Easton, Critical realism in case study research, Ind. Mark. Manag. 39 (1) (2010) 118–128, https://doi.org/10.1016/j.indmarman.2008.06.004.
[60] J.A. Maxwell, Using qualitative methods for causal explanation, Field Methods 16 (3) (2004) 243–264, https://doi.org/10.1177/1525822X04266831.
[61] H. Smyth, S. Pryke, Collaborative Relationships in Construction, Blackwell Publishing, 978-1405180412, 2008 ISBN.
[62] H. Smyth, Developing trust, in: H. Smyth, S. Pryke (Eds.), Collaborative Relationships in Construction, Blackwell Publishing, 2008, pp. 129–160, , https://doi.org/10.1002/9781444301069.
[63] S. Fox, Getting real about BIM: critical realist descriptions as an alternative to the naïve framing and multiple fallacies of hype, Int. J. Manag. Proj. Bus. 7 (3) (2014) 405–422, https://doi.org/10.1108/IJMPB-12-2013-0073.
[64] BIMei. (2017b). 291in conceptual BIM ontology | the BIMe initiative. Retrieved from https://bimexcellence.org/resources/200series/291in-conceptual-bim-ontology/. Last accessed, Sep 23, 2019.
[65] BIMdictionary, BIM dictionary platform | by the BIMe initiative, Retrieved from, 2013. https://BIMdictionary.com.
[66] Oxford. (2018). "information" - compact Oxford English dictionary. Compact Oxford English Dictionary. Retrieved from https://en.oxforddictionaries.com/definition/information. Last accessed, July 5, 2018.
[67] ISO/IEC, ISO/IEC DIS 2382–36 Information Technology – Vocabulary - Part 36: Learning, Education and Training, Retrieved from, 2016. https://www.iso.org/standard/63996.html.
[68] ISO, ISO 22263:2008 Organization of Information about Construction Works - Framework for Management of Project Information, Retrieved from, 2008. https://www.iso.org/standard/40835.html.
[69] ISO, ISO 6707–1:2017 Buildings and Civil Engineering Works — Vocabulary - Part 1: General Terms, Retrieved from, 2017. https://www.iso.org/standard/72244.html.
[70] S.C.W. Kong, H. Li, Y. Liang, T. Hung, C. Anumba, Z. Chen, Web services enhanced interoperable construction products catalogue, Autom. Constr. 14 (3) (2005) 343–352, https://doi.org/10.1016/j.autcon.2004.08.008.
[71] A. Mathes, Folksonomies - Cooperative Classification and Communication through Shared Metadata. Computer Mediated Communication, LIS590CMC (Doctoral Seminar), Graduate School of Library and Information Science, Retrieved from, 2004. http://www.adammathes.com/academic/computer-mediatedcommunication/folksonomies.html.
[72] K.K. Fallon, M.E. Palmer, General Buildings Information Handover Guide: Principles, Methodology and Case Studies, Retrieved from, 2007. https://www.nist.gov/publications/general-buildings-information-handover-guide.
[73] Wikipedia. (2019). Unstructured data. Retrieved from https://en.wikipedia.org/wiki/Unstructured_data. Last accessed, September 21, 2019.
[74] X. Li, W. Yi, H.-L. Chi, X. Wang, A.P. Chan, A critical review of virtual and augmented reality (VR/AR) applications in construction safety, Autom. Constr. 86 (2018) 150–162, https://doi.org/10.1016/j.autcon.2017.11.003.
[75] G. Atsali, S. Panagiotakis, E. Markakis, G. Mastorakis, C.X. Mavromoustakis, E. Pallis, A. Malamos, A mixed reality 3D system for the integration of X3DoM graphics with real-time IoT data, Multimed. Tools Appl. 77 (4) (2018) 4731–4752, https://doi.org/10.1007/s11042-017-4988-z.
[76] F. Rodhain, B. Fallery, What is information requirement? A constructivism versus a positivism perspective, in: D. Jawahar (Ed.), Emerging Issues in Management Research, EXCEL BOOKS, 2008, pp. 1–20 Retrieved from https://hal.archives-ouvertes.fr/hal-00777812.
[77] H.B. Cavka, S. Staub-French, E.A. Poirier, Developing owner information requirements for BIM-enabled project delivery and asset management, Autom. Constr. 83 (2017) 169–183, https://doi.org/10.1016/j.autcon.2017.08.006.
[78] L. Walras, Éléments d'économie politique pure, ou, Théorie de la richesse sociale, 1 R. Pichon et R. Durand-Auzias, Paris, 1926.
[79] ISO, Facility Management - Management Systems - Requirements with Guidance for Use, Retrieved from, 2018. https://www.iso.org/standard/68021.html.
[80] ISO, ISO/DIS 19650–1: Organization of Information about Construction Works - Information Management Using Building Information Modelling - Part 1: Concepts and Principles, Retrieved from, 2018. https://www.iso.org/standard/68078.html.
[81] M. Müller, C. Schurr, Assemblage thinking and actor-network theory: conjunctions, disjunctions, cross-fertilisations, Trans. Inst. Br. Geogr. 41 (3) (2016) 217–229, https://doi.org/10.1111/tran.12117.
[82] N. Castree, False antitheses? Marxism, nature and actor-networks, Antipode 34 (1) (2002) 111–146, https://doi.org/10.1111/1467-8330.00228.
[83] B. Succar, N. Saleeb, W. Sher, Model Uses: Foundations for a Modular Requirements Clarification Language. Paper Presented at the Australasian Universities Building Education (AUBEA2016), Cairns, Australia, https://www.researchgate.net/profile/Bilal_Succar/publication/303013287_Model_Uses_Foundations_for_a_Modular_Requirements_Clarification_Language/links/57355e9908ae298602df0f5f.pdf, (2016).
[84] ISO, ISO 14050:2009 Environmental Management - Vocabulary, Retrieved from, 2009. https://www.iso.org/standard/41492.html.
[85] ISO, ISO 9000:2015 Quality Management Systems - Fundamentals and Vocabulary, Retrieved from, 2015. https://www.iso.org/standard/45481.html.
[86] ISO, ISO 29481-1:2016 Building Information Models - Information Delivery Manual - Part 1: Methodology and Format, Retrieved from, 2016. https://www.iso.org/standard/60553.html.
[87] ISO/IEC, ISO/IEC 2382:2015 Information Technology - Vocabulary, Retrieved from, 2015. https://www.iso.org/standard/63598.html.
[88] J. Gubbi, R. Buyya, S. Marusic, M. Palaniswami, Internet of things (IoT): a vision, architectural elements, and future directions, Futur. Gener. Comput. Syst. 29 (7) (2013) 1645–1660, https://doi.org/10.1016/j.future.2013.01.010.
[89] J.F. Sowa, J.A. Zachman, Extending and formalizing the framework for information systems architecture, IBM Syst. J. 31 (3) (1992) 590–616, https://doi.org/10.1147/sj.313.0590.
[90] BIMFramework. (2016). Project Information Taxonomy | BIM Framework Blog - Post 40 | the BIMe Initiative. Retrieved from https://www.bimframework.info/2016/06/project-information-taxonomy.html. Last accessed, Sep 23, 2019.
[91] B. Succar, Building information Modelling maturity matrix, in: J. Underwood, U. Isikdag (Eds.), Handbook of Research on Building Information Modelling and Construction Informatics: Concepts and Technologies, Information Science Reference, IGI Publishing, 2010, pp. 65–103, , https://doi.org/10.4018/978-1-60566-928-1.ch004.
[92] M. Kassem, G. Kelly, N. Dawood, M. Serginson, S. Lockley, BIM in facilities management applications: a case study of a large university complex, Built Environment Project and Asset Management 5 (3) (2015) 261–277, https://doi.org/10.1108/BEPAM-02-2014-0011.
[93] P.E. Love, J. Matthews, I. Simpson, A. Hill, O.A. Olatunji, A benefits realization management building information modeling framework for asset owners, Autom. Constr. 37 (2014) 1–10, https://doi.org/10.1016/j.autcon.2013.09.007.
[94] Edirisinghe, R., London, K., Kalutara, P., & Aranda-Mena, G. Building Information Modelling for Facility Management: Are We There Yet? doi:https://doi.org/10.1108/ECAM-06-2016-0139.
[95] Y. Arayici, T. Onyenobi, C. Egbu, Building information modelling (BIM) for facilities management (FM): the MediaCity case study approach, International Journal of 3D Information Modelling 1 (1) (2012) 55–73 Retrieved from http://www.igi-global.com/article/building-informa.
[96] A.X. Sanchez, K.D. Hampson, S. Vaux, Delivering Value with BIM: A Whole-of-Life Approach, Routledge, 2016.
[97] SBEnrc. (2017). BIM Value Tool | by the Australian Sustainable Built Environment National Research Centre (SBEnrc) | Part of Project 2.34, Driving Whole-of-Life Efficiencies through BIM and Procurement | Hosted by NATSPEC. Retrieved from https://bimvaluetool.natspec.org/. Last accessed, June 8, 2018.
[98] G. Ballard, The Lean Project Delivery System: An Update, Retrieved from, Lean Construction Journal (2008) 1–19 https://www.leanconstruction.org/learning/publications/lean-construction-journal/lcj-back-issues/2008-issue/.
[99] BIMei, 211in Model Uses List | the BIMe Initiative, Retrieved from, 2017. http://bimexcellence.org/resources/200series/211in/.
[100] J. Messner, C. Anumba, C. Dubler, S. Goodman, C. Kasprzak, R. Kreider, … N. Zikic, BIM Project Execution Planning Guide v2.2, Retrieved from, 2019. https://www.bim.psu.edu/bim_pep_guide/.
[101] R.H. Lowe, M.F. D'Onofrio, D.M. Fisk, O. Seppänen, A Comparison of Location-Based Scheduling with the Traditional Critical Path Method: American College of Construction Lawyers 2012 Annual Meeting, San Francisco, CA, USA, (2012).
[102] S. Matos, E. Lopes, Prince2 or PMBOK–a question of choice, Procedia Technology 9 (2013) 787–794, https://doi.org/10.1016/j.protcy.2013.12.087.
[103] L. Koskela, Lean production in construction. Paper Presented at the 10th International Symposium on Automation and Robotics in Construction (ISARC), Houston, Texas, USA, https://pdfs.semanticscholar.org/a8ca/2b5a2ec037abb36b6be733e2f50737d1211b.pdf, (1997).
[104] O. Salem, J. Solomon, A. Genaidy, I. Minkarah, Lean construction: from theory to implementation, J. Manag. Eng. 22 (4) (2006) 168–175, https://doi.org/10.1061/%28ASCE%290742-597X%282006%2922%3A4%28168%29.
[105] M.F. Tchidi, Z. He, Y.B. Li, Process and quality improvement using six sigma in construction industry, Journal of Civil Engineering & Management 18 (2) (2012) 158–172, https://doi.org/10.3846/13923730.2012.657411.
[106] CIB/TG33, Concurrent engineering in construction, Paper Presented at the Proceedings of the Third International Conference on Concurrent Engineering in Construction, University of California, Berkeley, United States, 20021-2 July, 2002. Retrieved from http://www.academia.edu/download/31048501/CEC02_Proceedings.pdf.
[107] ISO, ISO/DIS 19650–2: Organization of Information about Construction - Information Management Using Building Information Modelling - Part 2: Delivery Phase of the Assets, Retrieved from, 2018. https://www.iso.org/standard/68080.html.
[108] L. Swanson, Linking maintenance strategies to performance, Int. J. Prod. Econ. 70 (3) (2001) 237–244, https://doi.org/10.1016/S0925-5273(00)00067-0.
[109] O.O. Aremu, A. Salvador Palau, D. Hyland-Wood, A.K. Parlikad, P.R. McAree, Structuring data for intelligent predictive maintenance in asset management, Paper Presented at the 2018 IFAC Symposium on Information Control Problems in Manufacturing (INCOM 2018), Bergamo, Italy, 2018, https://doi.org/10.1016/j.ifacol.2018.08.370.
[110] NBS, UniClass 2015, Retrieved from, 2015. https://buildig.com/uniclass-2015/.
[111] T. Adeline Zhu Teng, Z. Atiq, S. Monty, Enabling an effective knowledge and information flow between the phases of building construction and facilities

management, Facilities 36 (3/4) (2018) 151–170, https://doi.org/10.1108/F-03-2016-0028.
[112] COBie, Construction Operation Building Information Exchange (COBie) | National BIM Standards - United States v3, Retrieved from, 2015. https://www.nationalbimstandard.org/files/NBIMS-US_V3_4.2_COBie.pdf.
[113] G.Ó. Aðalsteinsson, Feasibility Study on the Application of BIM Data for Facility Management, Retrieved from, 2014. http://hdl.handle.net/1946/19391.
[114] K.K. Fallon, M.E. Palmer, Capital facilities information handover guide, part 1, Retrieved from, 2006. https://www.nist.gov/publications/capital-facilities-information-handover-guide-part-1.
[115] BIMFramework, Asset Hierarchy (Updated Aug 9, 2019) | BIM Framework Blog - Post 30 | the BIMe Initiative, Retrieved from, 2019. https://www.bimframework.info/2019/08/asset-hierarchy.html.
[116] M. Naim, J. Barlow, An innovative supply chain strategy for customized housing, Constr. Manag. Econ. 21 (6) (2003) 593–602, https://doi.org/10.1080/0144619032000134129.
[117] R.L. Owen, L. Koskela, Agile construction project management, Paper Presented at the 6th International Postgraduate Research Conference in the Built and Human Environment, 2006 Retrieved from http://usir.salford.ac.uk/id/eprint/10005.
[118] K. Kim, Y. Cho, K. Kim, BIM-driven automated decision support system for safety planning of temporary structures, J. Constr. Eng. Manag. 144 (8) (2018) 04018072https://doi:10.1061/(ASCE)CO.1943-7862.0001519.
[119] M. Mangal, J.C.P. Cheng, Automated optimization of steel reinforcement in RC building frames using building information modeling and hybrid genetic algorithm, Autom. Constr. 90 (2018) 39–57, https://doi.org/10.1016/j.autcon.2018.01.013.
[120] S. Zhang, J. Teizer, J.-K. Lee, C.M. Eastman, M. Venugopal, Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules, Autom. Constr. 29 (2013) 183–195, https://doi.org/10.1016/j.autcon.2012.05.006.
[121] Y. Ji, F. Leite, Automated tower crane planning: leveraging 4-dimensional BIM and rule-based checking, Autom. Constr. 93 (2018) 78–90, https://doi.org/10.1016/j.autcon.2018.05.003.
[122] W. Chen, K. Chen, J.C.P. Cheng, Q. Wang, V.J.L. Gan, BIM-based framework for automatic scheduling of facility maintenance work orders, Autom. Constr. 91 (2018) 15–30, https://doi.org/10.1016/j.autcon.2018.03.007.
[123] S. Yarmohammadi, If these Walls Could Talk: Automated Performance Measurement for Building Modeling Decisions Using Data Analytics, Georgia Institute of Technology, 2018 Retrieved from https://smartech.gatech.edu/handle/1853/59812.
[124] K. Petersen, R. Nagpal, J. Werfel, Termes: An autonomous robotic system for three-dimensional collective construction, Proc. Robotics: Science & Systems VII, 2011, https://doi.org/10.15607/RSS.2011.VII.035.
[125] K. Petersen, R. Nagpal, Complex design by simple robots: a collective embodied intelligence approach to construction, Archit. Des. 87 (4) (2017) 44–49, https://doi.org/10.1002/ad.2194.
[126] H. Hamann, Scenarios of swarm robotics, Swarm Robotics: A Formal Approach, Springer International Publishing, Cham, 2018, pp. 65–93, , https://doi.org/10.1007/978-3-319-74528-2_4.
[127] R. Fernando, R. Drogemuller, A. Burden, Parametric and Generative methods with BuildinG information modellinG. Paper Presented at the CAADRIA 2012: Beyond Codes and Pixels, Chennai, India, https://cumincad.architexturez.net/system/files/pdf/caadria2012_089.content.pdf, (2012).
[128] S. Abrishami, J. Goulding, F.P. Rahimian, A. Ganah, Integration of BIM and generative design to exploit AEC conceptual design innovation, Information Technology in Construction 19 (2014) 350–359 Retrieved from http://www.itcon.org/2014/21.
[129] G.P. Monizza, C. Bendetti, D.T. Matt, Parametric and generative design techniques in mass-production environments as effective enablers of industry 4.0 approaches in the building industry, Autom. Constr. 92 (2018) 270–285, https://doi.org/10.1016/j.autcon.2018.02.027.
[130] B.R.K. Mantha, C.C. Menassa, V.R. Kamat, Robotic data collection and simulation for evaluation of building retrofit performance, Autom. Constr. 92 (2018) 88–102, https://doi.org/10.1016/j.autcon.2018.03.026.
[131] L. Lau, Y. Quan, J. Wan, N. Zhou, C. Wen, N. Qian, F. Jing, An autonomous ultra-wide band-based attitude and position determination technique for indoor mobile laser scanning, ISPRS Int. J. Geo Inf. 7 (4) (2018) 155, https://doi.org/10.3390/ijgi7040155.
[132] H. Freimutha, J. Müllera, M. Königa, Simulating and Executing UAV-Assisted Inspections on Construction Sites. Paper Presented at the 34rd ISARC, Taipei, Taiwan, (2017), https://doi.org/10.22260/ISARC2017/0090.
[133] C. Xiao, Y. Liu, A. Akhnoukh, Bibliometric Review of Artificial Intelligence (AI) in Construction Engineering and Management. Paper Presented at the International Conference on Construction and Real Estate Management (ICCREM) - Innovative Technology and Intelligent Construction, California, USA, https://ascelibrary.org/doi/abs/10.1061/9780784481721.004, (2018).
[134] F. Biljecki, Level of Detail in 3D City Models. (PhD July 28, 2017), Delft University of Technology, 2017 Retrieved from https://www.narcis.nl/publication/RecordID/oai:tudelft.nl:uuid%3Af12931b7-5113-47ef-bfd4-688aae3be248.
[135] J. Jokela, CityGML Building Model Production from Airborne Laser Scanning (Masters Thesis), Aalto University, 2016 Retrieved from http://urn.fi/URN:NBN:fi:aalto-201602161355.
[136] L. Onnasch, C.D. Wickens, H. Li, D. Manzey, Human performance consequences of stages and levels of automation: an integrated meta-analysis, Hum. Factors 56 (3) (2014) 476–488, https://doi.org/10.1177/0018720813501549.
[137] J. Frohm, V. Lindström, M. Winroth, J. Stahre, Levels of automation in manufacturing, Ergonomia-an International journal of ergonomics and human factors 30 (3) (2008) Retrieved from http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A216233&dswid=7151.
[138] R. Parasuraman, T.B. Sheridan, C.D. Wickens, A model for types and levels of human interaction with automation, IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans 30 (3) (2000) 286–297, https://doi.org/10.1109/3468.844354.
[139] Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: approaches to the development and implementation of building information modeling. Autom. Constr., 43(0), 84–91. doi: doi:https://doi.org/10.1016/j.autcon.2014.03.009.
[140] N. Rosenberg, Why technology forecasts often fail, The Futurist 29 (1995) 16 Retrieved from https://www.questia.com/magazine/1G1-17100211/why-technology-forecasts-often-fail.
[141] F.C. Köseci, Integrated Life Cycle Assessment (LCA) to Building Information Modelling (BIM), Retrieved from, 2018. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1229841&dswid=-956.
[142] J.D. Silvestre, N. Pargana, J. de Brito, M.D. Pinheiro, V. Durão, Insulation Cork boards—environmental life cycle assessment of an organic construction material, Materials 9 (5) (2016) 394, https://doi.org/10.3390/2Fma9050394.
[143] K. Adams, M. Osmani, T. Thorpe, J. Thornback, Circular Economy in Construction: Current Awareness, Challenges and Enablers, (2017), https://doi.org/10.1680/jwarm.16.00011.
[144] F. Pomponi, A. Moncaster, Circular economy for the built environment: a research framework, J. Clean. Prod. 143 (2017) 710–718, https://doi.org/10.1016/j.jclepro.2016.12.055.
[145] M. Lieder, A. Rashid, Towards circular economy implementation: a comprehensive review in context of manufacturing industry, J. Clean. Prod. 115 (2016) 36–51, https://doi.org/10.1016/j.jclepro.2015.12.042.
[146] T. Streule, N. Miserini, O. Bartlomé, M. Klippel, B.G. de Soto, Implementation of scrum in the construction industry, Procedia Engineering 164 (2016) 269–276, https://doi.org/10.1016/j.proeng.2016.11.619.
[147] H.F. Cervone, Understanding agile project management methods using Scrum, OCLC Systems & Services: International Digital Library Perspectives 27 (1) (2011) 18–22, https://doi.org/10.1108/10650751111106528.
[148] M. Poppendieck, T. Poppendieck, Lean Software Development: An Agile Toolkit, Addison-Wesley, 978-0133812961, 2003.
[149] L. Koskela, G. Howell, The theory of project management: Explanation to novel methods, Paper Presented at the Proceedings IGLC, 2002 Retrieved from https://pdfs.semanticscholar.org/b426/4577bc3c4258cc9cc6331ea4e733a3d29ef7.pdf.
[150] ISO, ISO 37500:2014 Guidance on Outsourcing, Retrieved from, 2014. https://www.iso.org/standard/56269.html.
[151] H.-B. Jun, D. Kiritsis, P. Xirouchakis, Research issues on closed-loop PLM, Comput. Ind. 58 (8–9) (2007) 855–868, https://doi.org/10.1016/j.compind.2007.04.001.
[152] B. Dave, S. Kubler, K. Främling, L. Koskela, Opportunities for enhanced lean construction management using internet of things standards, Autom. Constr. 61 (2016) 86–97, https://doi.org/10.1016/j.autcon.2015.10.009.
[153] BIMFramework. (2014). Knowledge Content Taxonomy | BIM Framework Blog - Post 25 | the BIMe Initiative. Retrieved from https://www.bimframework.info/2014/07/knowledge-content-taxonomy.html. Last accessed, Sep 23, 2019.
[154] M. Kassem, B. Succar, N. Dawood, Building information modeling: analyzing noteworthy publications of eight countries using a knowledge content taxonomy, in: R. Issa, S. Olbina (Eds.), Building Information Modeling: Applications and Practices in the AEC Industry, University of Florida: ASCE Press, 2014, , https://doi.org/10.1061/9780784413982.ch13 production.
[155] BIMFramework, Project Lifecycle Phases | BIM Framework Blog - Post 8 | the BIMe Initiative, Retrieved from, 2013. https://www.bimframework.info/2013/12/project-lifecycle-phases.html.
[156] bSI, Infrastructure asset managers BIM requirements technical report (TR 1010), Retrieved from, 2018. https://www.buildingsmart.org/wp-content/uploads/2018/01/18-01-09-AM-TR1010.pdf.
[157] buildingSMART. (2013). Overview of information delivery manuals independent of their status. Retrieved from http://iug.buildingsmart.org/idms/overview. Last accessed, June 14, 2018.
[158] ISO/IEC, ISO/IEC 19510:2013 Information Technology - Object Management Group Business Process Model and Notation, Magazine, Volume. Retrieved from, 2013. https://www.iso.org/standard/62652.html.
[159] BIMdictionary, Granularity level, Online BIM Dictionary, 2019 Retrieved from https://bimdictionary.com/en/granularity-level/1 (Last accessed, Dec 29, 2019).
[160] B. Succar, W. Sher, A. Williams, Measuring BIM performance: five metrics, Architectural Engineering and Design Management 8 (2) (2012) 120–142, https://doi.org/10.1080/17452007.2012.659506.
[161] ANSI. (2018). American National Standards Institute (ANSI). Retrieved from https://www.ansi.org/. Last accessed, June 24, 2018.
[162] NEC. (2018). New engineering contract (NEC) | Institution of Civil Engineers, Retrieved from https://www.neccontract.com/. Last accessed, June 24, 2018.
[163] FIDIC. (2018). International Federation of Consulting Engineers | Contracts. Retrieved from http://fidic.org/. Last accessed, May 29, 2018.
[164] OmniClass, OmniClass | Construction Classification System, Retrieved from, 2013. http://www.omniclass.org/.
[165] CoClass. (2018). CoClass, Swedish Classification System for all Built Environments. Retrieved from https://byggtjanst.se/tjanster/coclass/. Last accessed, May 29, 2018.
[166] L. Atzori, A. Iera, G. Morabito, The internet of things: a survey, Comput. Netw. 54 (15) (2010) 2787–2805, https://doi.org/10.1016/j.comnet.2010.05.010.
[167] C. Perera, A. Zaslavsky, P. Christen, D. Georgakopoulos, Context aware computing for the internet of things: a survey, IEEE Communications Surveys & Tutorials 16

(1) (2014) 414–454 https://ieeexplore.ieee.org/document/6512846.

[168] A. Hevner, S. Chatterjee, Design science research in information systems, Design Research in Information Systems: Theory and Practice, Springer US, Boston, MA, 2010, pp. 9–22, , https://doi.org/10.1007/978-1-4419-5653-8_2.

[169] J.E. Taylor, R.E. Levitt, A new model for systemic innovation diffusion in project-based industries, Paper Presented at the Project Management Institute International Research Conference, 2004 Retrieved from https://cife.stanford.edu/new-model-systemic-innovation-diffusion-project-based-industries.

[170] C. Harty, Innovation in construction: a sociology of technology approach, Building Research & Information 33 (6) (2005) 512–522, https://doi.org/10.1080/09613210500288605.

[171] E.A. Pärn, D.J. Edwards, M.C.P. Sing, Origins and probabilities of MEP and structural design clashes within a federated BIM model, Autom. Constr. 85 (2018) 209–219, https://doi.org/10.1016/j.autcon.2017.09.010.

[172] J. Potužák, Utilization of Lean Construction Principles and Techniques in the Czech Republic (Masters Thesis), Retrieved from,, 2018. https://dspace.cvut.cz/handle/10467/74252.

[173] P.A. Zadeh, G. Wang, H.B. Cavka, S. Staub-French, R. Pottinger, Information quality assessment for facility management, Adv. Eng. Inform. 33 (2017) 181–205, https://doi.org/10.1016/j.aei.2017.06.003.

[174] Maheshwary, J. (2018). Interactive Visual Analytics for BIM Compliance Assessment and Design Decision-Making. (Master's), University of British Columbia, Retrieved from https://open. library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0370964.

[175] A. Cameron-Huff, How Tokenization Is Putting Real-World Assets on Blockchains | Nasdaq, Retrieved from, 2017. https://www.nasdaq.com/article/how-tokenization-is-putting-real-world-assets-on-blockchains-cm767952.

[176] B. Levin, Potential for Cryptocurrency to Fund Investment in Sustainable Real Assets. (Environmental Management degree Masters Project), Nicholas School of the Environment of Duke University, 2018 Retrieved from https://coinrivet.com/fr/research/papers/potential-for-cryptocurrency-to-fund-investment-in-sustainable-real-assets/.

[177] J. Chen, E. Pan, Tokenized Hardware: The New Crypto Innovation, Retrieved from, 2018. https://flowchain.co/Tokenized-Hardware-WhitePaper.pdf.

[178] S. Austin, A. Baldwin, A. Newton, Manipulating the flow of design information to improve the programming of building design, Construction Management and Economics 0144-6193, 12 (5) (1994) 445–455, https://doi.org/10.1080/01446199400000054.