NATIONAL DIGITAL TWIN PROGRAMME

An integrated approach to information management

Identifying decisions and the information required for them using activity and process models

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Contents

1. Introduction and Purpose

If we are to achieve more from the built environment, it is essential that we better understand the information required in its planning, design, construction and management. In addition, this information needs to be able to be shared and aggregated in a way that is effective, resilient and secure. This is critical not only for improving the way we deliver new built assets and manage them through their lifecycle, but also for meeting other requirements such as carbon reduction and climate resilience.

A formal mechanism to ensure that the right information can be made available at the right time, to the right people and that the quality of the information is known and understood, is required. The Information Management Framework (IMF) (1) is such a mechanism.

Fulfilling the promise of information that is of a quality that ensures that it “is fit for purpose for the decisions it supports” (1) requires a rigorous approach to the analysis of activities and decisions on which they depend. This

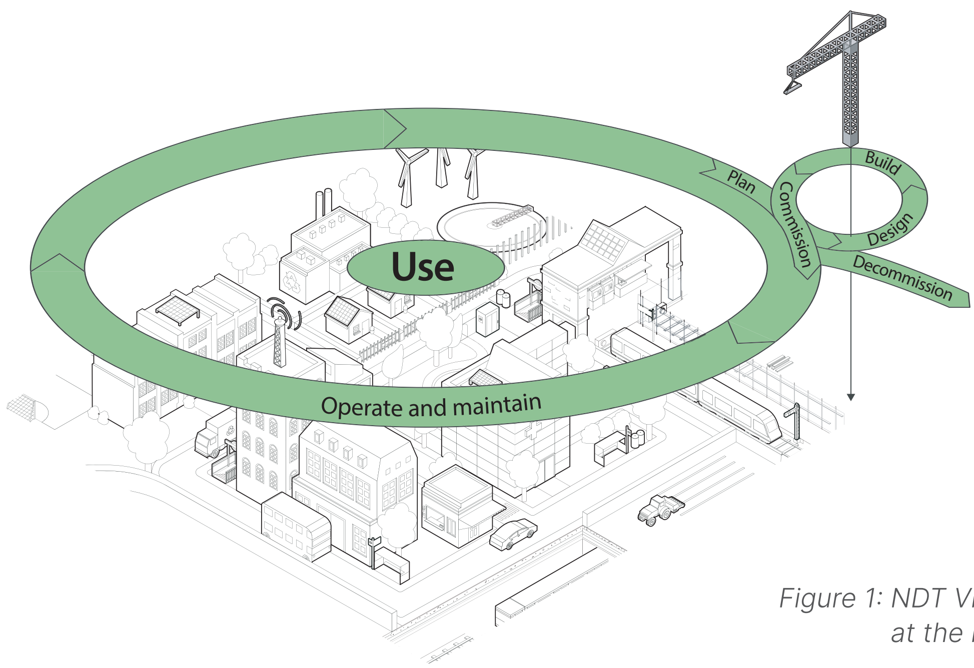

Figure 1: NDT Vision depends on data at the right quality.

in turn requires a method of translating the analysis to a clear, implementable set of information requirements.

Starting with the approach outlined in this document, an effective route to knowing what the information quality requirements are ensures that best use is made of the IMF in the management of that information and the decisions subsequently relying upon it. The purpose of this document is to introduce the analysis of lifecycle activity to identify the need for information of sufficient detail to ensure that it is fit for this purpose, in particular for the lifecycle of large Built Asset Systems. This approach can be used by any organisation for any purpose that requires data of the right quality to be created and used. Thus its use is vital to the use of the IMF to enable an integrated, trusted and enduring National Digital Twin.

This document introduces an objective approach to analysing activity and outlines two general process models – a Built Asset System lifecycle and a periodic process lifecycle – to support the management of information for any large system of people, organisations, assets and, crucially, the activities in which they are involved. These are referred to as “lifecycle” processes because they are intended to capture the complete range of activity that can result from their realisation and of which there is a need to create and use data. As systems increase in complexity the role of professional Systems Engineering is recognised as important in infrastructure projects. Information is vital to the success of Systems Engineering activity too and this document illustrates how this can be achieved.

Two lifecycle processes have been selected to set the context for integrated information management and support the creation and use of the Information Management Framework (IMF) as part of the National Digital Twin programme (NDT), see Figure 1. In particular, the processes are aimed at enabling information requirement capture for any and all points in the lifecycle of the assets and systems to which the Digital Twins relate and the subsequent meeting of these requirements in an integrated and enduring manner. Through the analytic techniques and the process models covered in this document there is the potential to identify the information required to support the activities and organisations that depend upon them and ensure that decisions made during these processes are not undermined by data that are not of the required quality.

The document also provides a worked example of the analysis of an activity that is relevant to the engineering found in the built environment sector, particularly construction. The example has been chosen to illustrate the analysis of activity and concludes with some general observations. As such it aims to offer an introduction to activity modelling and explain its role in the improved management of information – a shared goal of the NDT, Smart Infrastructure projects and wider UK ambitions for the use of data for the nation’s benefit.

2. Introducing Activity Modelling

This introductory Chapter starts by providing some key terms that will be used frequently in the document and then introduces the need for activity and process models. A key point to note with some of the terms, like "activity", used in this document is that they are used in ways that are generalised to a degree that can initially seem unfamiliar. They are given this careful treatment to enable them to be clearly and consistently employed in any circumstance that requires their use for the purposes of conducting this lifecycle analysis. This approach also paves a way for the application of the IMF's Foundation Data Model (FDM) and Reference Data Library (RDL) to achieve an acceptable quality in the data that should follow this integrated information requirements methodology.

Requirements Matter

If requirements are not identified and agreed, it is inevitable that there will be a significant chance of their not being met. This is particularly true of information requirements, but it is rare that sufficient attention is given to them. The analytic approach in this document introduces a methodology for the identification of information requirements for any application.

Before introducing some terms that require this care the point made in the last paragraph can be illustrated by clarifying how this document treats "activity". It is a familiar word and is put to good use in many contexts. A common use, for example in the areas of project, construction and facilities management, is to cover tasks performed by humans with additional resources where required to achieve an outcome (such as a deliverable). Dictionary definitions[1] typically include this but admit other uses (e.g. sports activity, terrorist activity, economic activity and "all human activity" are all allowable uses). What about something that happens* without human control or involvement (such as the weather, chemical reaction or a simulation that can take days to run without human supervision)? These are all relevant to tasks that humans perform and call "activity" and also involve something's happening. Thus a wide use of the term "activity" is desirable if we want to accommodate any activity that may be relevant to our information requirements.

The first lesson for activity modelling is to ensure that there is sufficient clarity on what "activity" is, or can be, and that this should set the tone for the analysis of activity itself. Other terms that require similar care are introduced in the next subsection.

2.1 Setting the scene

As introduced at the start of this section, providing clarity of some vital terms is necessary to minimise ambiguity in the analysis of activity. Since the goal is consistency in the data supporting these activities, and the processes derived from the analysis, care has been taken over the use of specific terms relating to them. Deeper insight can be found in the documentation for the Top Level Ontology choices for and the specification of the IMF Foundation Data Model (FDM) (2). However, no specialist knowledge of the FDM is needed to read this document but it will help those conducting detailed analysis and implementing information systems based on it.

The following terms are informally introduced here to avoid assumptions' about their use from different uses in existing industry standards and related documents.

- **Activity:** This is used to describe something that happens, bringing about change. As illustrated at the start of this section this could be wide-ranging. Activity involving humans is just one sort of activity that is in scope for activity modelling. As with humans, all participants in the activity have a role.
- **Particular:** This is used to refer to an individual item. This document, and the FDM, rely on each particular's being a distinct thing existing in space and time.
- **Plan:** Plans are vital to the conduct of particular lifecycle activities. For this document a plan is an intended course of action, but can also include models of that particular, future activity. Planning is an activity that requires both good information and decisions and, as a result, supports the particular course of action that is based upon it.
- **Process:** Some dictionary definitions of "process" overlap with those of both "activity " and "plan". This document is focussed mainly on an organisational context for processes, sometimes called Business Processes. A business process is thus a prescription for activities that may be required to ensure that one or more agreed outcome results if it is realised by suitable activity. This suits the organisational use of the term "process" as in: "Follow corporate process X for this large procurement activity Y.".
- **System:** A dictionary definition is "a set of connected things or devices that operate together"[2]. For engineered systems, in particular Infrastructure systems, this can include a very large number of component parts, people and organisations that are intended to operate / function well together. Built Asset Systems, addressed /considered in this document, are examples of this in which there is a significant role for large, engineered components that are intended to work together as a whole. Such systems can be part of or depend on other systems (e.g. a waste water treatment plant can be a system that is part of a wider regional waste water treatment system. It can also depend on electricity provided to it by a national or regional electric power system.).

A further term, "lifecycle", is worth mention. From research in support of this work it is clear that there are many uses of the term "lifecycle" in project, programme, portfolio, product, organisational, and asset management. See (3) for a good guide to some of these uses. Not all of these cover the entire lifecycle of the system or activity that they are focussed on, but they all share a goal of seeing the thing to which they refer from its start to a satisfactory conclusion.

When considering information management the goal is similar but to make full and effective use of data a whole-lifecycle view of the thing(s) to which the required information relates is needed. Constraining this view limits the potential of information capture and reuse. This would not only be costly, requiring duplication of information management activities and reduced information quality, but would also undermine the goal of supporting the national need for decisions made from data of the right quality.

The aim is therefore to be able to address the relevant lifecycle aspects of any and all participants in an activity. Each of these participants will, in turn, have a lifecycle that may require analysis to reveal more of the required information. Following the process of information requirement capture as a result of the methods introduced in this document existing lifecycle models, such as those in (3), can still be used as originally intended, with the added benefit of having data of the right quality.

The reason two lifecycle process models have been chosen for analysis is that there are two areas in which organisations find themselves that merit generalisation:

1. Managing (large) Built Assets as functional systems:
   Many large organisations must plan for and actively manage their dependence on assets such as buildings, infrastructure such as transport and energy systems, maintenance facilities, production or operational facilities, storage and logistics assets, data centres, etc.

   At almost all scales the need for some or all of these assets requires planning, business commitment and an ability to finance them well in advance of their being operational. The lifetime costs and value derived from them once in operation are critical to the performance of the organisations and, typically, those who depend on the organisation (be it a government department or a manufacturer of specialist equipment for export). When a new asset is brought into being or an existing one is upgraded there is a similar lifecycle of activity despite the specifics differing, such as different suppliers, skills and oversight.

   The role of information throughout this asset lifecycle is analysed to enable the information management to be addressed in a way that improves the outcomes and reduces waste over such extended lifecycles of potentially complex and critical systems. The composition of all the activity resulting in and involving Built Asset Systems is introduced as a Built Asset System lifecycle activity model.

2. The activities of organisations, both large and small, usually have periodic cycles to their core operations, and decisions made throughout; from mandated annual funding and reporting cycles to the periodic demands of the contractual obligations of the services that they provide (e.g. the terms and educational years of schools and universities, training and maintenance cycles of the Armed Forces, annual cycle of electrical power generation and/or transmission over a nation-wide power grid, and timetabled passenger rail services).

   The focus of such organisational drivers is often one of continuity (to remain in operation), perhaps with a managed approach to performance improvement over successive cycles such as focus on an updated Vision or a desire to improve on some challenging Key Performance Indicators (KPIs). The composition of all the activity resulting in these operational cycles and, for the purposes of this document involving Built Asset Systems, is introduced as an operational lifecycle activity model.

These two lifecycle processes differ, but their application may require their being mutually informed by financial or performance information from a Built Asset System needed in the management and reporting cycle of a client or delivery organisation. The lifecycle processes will also support the core processes of one or more organisations. A core process will be one that is the top-level setting for all the other activity in the organisation. For a school this may be the process of delivering secondary level education to its pupils. For an energy network provider it may be the distribution of electrical energy from the transmission grid to consumers. This example shows that changes to the top level process (such as accommodating a more dynamic flow of energy in the distribution network) can influence many or all the lifecycle processes supporting that organisation.

The aim of introducing these models is to assist in the analysis of information requirements concerning the lifecycle activities of Built Asset Systems in the UK and the activities of organisations that depend upon them. The method is also generally applicable to other situations, but the focus of the NDT is the Built Environment including the Built Assets themselves. Without an integrated approach to process there is a poor basis for managing information, particularly if the goal is to integrate the use of that information in and between organisations that depend upon it.

2.2 Introduction to activity modelling

This document / paper / study* is intended to help those who are charged with the management of information relating to any part and, in aggregate, all of a Built Asset's lifecycle. Before introducing a process model to assist in this we shall explain why one is useful and explain how generic models can be created and used. Ultimately it is focussed on activity. If there is no activity, there is nothing to take note of; at least not of any concern as it is only through activity that change takes place. Given that all Built Assets arise because we intend them to, we should be very keen to ensure that the activity that is needed (and therefore also intended) to manage and benefit from them is effective.

To illustrate an approach to analysing the activity relevant to a particular Built Asset System (BAS), or part of it, we shall introduce a type of diagram that can aid in the analysis of what is going on. The Space-Time diagram allows us clearly to represent what is relevant to the scenario analysed. The use of these diagrams also helps in the translation from analysed information requirements to their representation in data; in our case this is directly compatible with the Foundation Data Model (FDM). The FDM treats each particular thing that is, or could be, real as a distinct region of space -time (a spatio-temporal region). It is fundamental to their identity (2).

Space-Time diagrams allow a convenient representation of the spatio-temporal things of interest that are involved in the analysis and subsequent representations in data (including properties relevant to them). Although they can initially appear unusual, they can become a great device for simplifying the analysis of all activities concerning Built Asset Systems. Although the Space Time diagrams in this document can appear sparse, and not cluttered, they can represent subjects of interest that are both complex and of any scale, provided they are distinct. A helpful way to think of an object shown in a Space Time diagram is that each box represents a state of that object for a period of time. It may be natural to think of states of physical things, particularly in an engineering or operational system context. Space-Time diagrams allow states to be clearly shown with the boundary between states being regions of interest to activity analysis because a change of state can require or produce information. The start and end of a particular state of an activity (or any state) will be marked by an event, an instant that marks the point at which the state changes, and in the analysis of activity that involved human tasks this is typically a decision. Further examples and background to the use of Space-Time diagrams the support of analysis can be found in (4) and (5).

An introductory Space-Time diagram is shown in Figure 1. It shows, as an example, an airport as a (typically large) Built Asset System. Although complex, the physical parts of the asset system can be grouped into a single whole if this is appropriate to the analysis. It is good to consider whether this is always the case, in light of real-world examples, and typically airports that function as such. Care is needed to consider what is and is not part of the physical, functional airport. This can become easier when it is decoupled from the typically complex mix of ownership, responsibilities, financing and regulation of parts of the airport system. This all comes out in the wash as the analysis is extended and the resulting clarity can help to demystify some of these areas and help ensure that data can be used effectively and appropriately throughout the activity lifecycle.

The diagram captures the unique existence of our example Airport extended in space and time. Of course, it may have some significant component parts (for example, an airfield with at least one runway, control tower, energy network, fuel storage and delivery equipment, cargo handling and storage, safety and emergency response infrastructure, aircraft maintenance areas, power systems, security assets, arrival and departure areas, parking and roads) but these are 'just' necessary parts of the airport that allow it to function as one.

If we want to create a new or significantly upgrade an existing airport, or operate it for at least the time committed in the business case, there will be a lot of activity required to result in and sustain it as a functioning airport system. We can represent the space-time extents of the activity involved in this functional airport, illustrated in Figure 2.

The diagram clearly shows that the aggregated activity that relates to the lifecycle of the airport spans a time beyond that of the airport system itself. The airport as a functioning system is only involved in the activity lifecycle for a (hopefully long) duration that is part of the total activity lifecycle. That involvement is indicated by the purple dashed box. Activity that happened earlier in the lifecycle of our example airport can have a significant bearing on the resulting function of all or parts of it subsequently.

Many of the physical system parts, put in place during implementation or during upgrade or maintenance, will be present in the system for many years so the data created on them should (where possible) be managed so that they can support

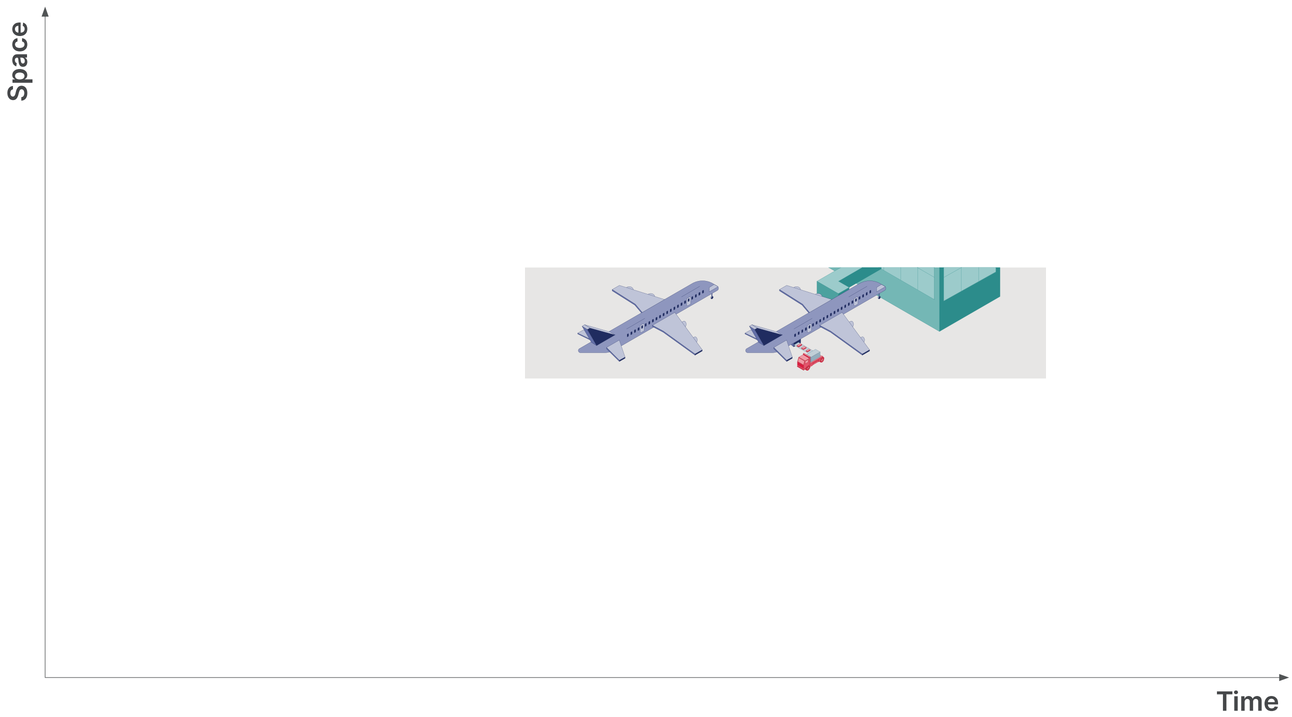

Figure 2: Space-time diagram of an Airport – An example Built Asset (Functional) System

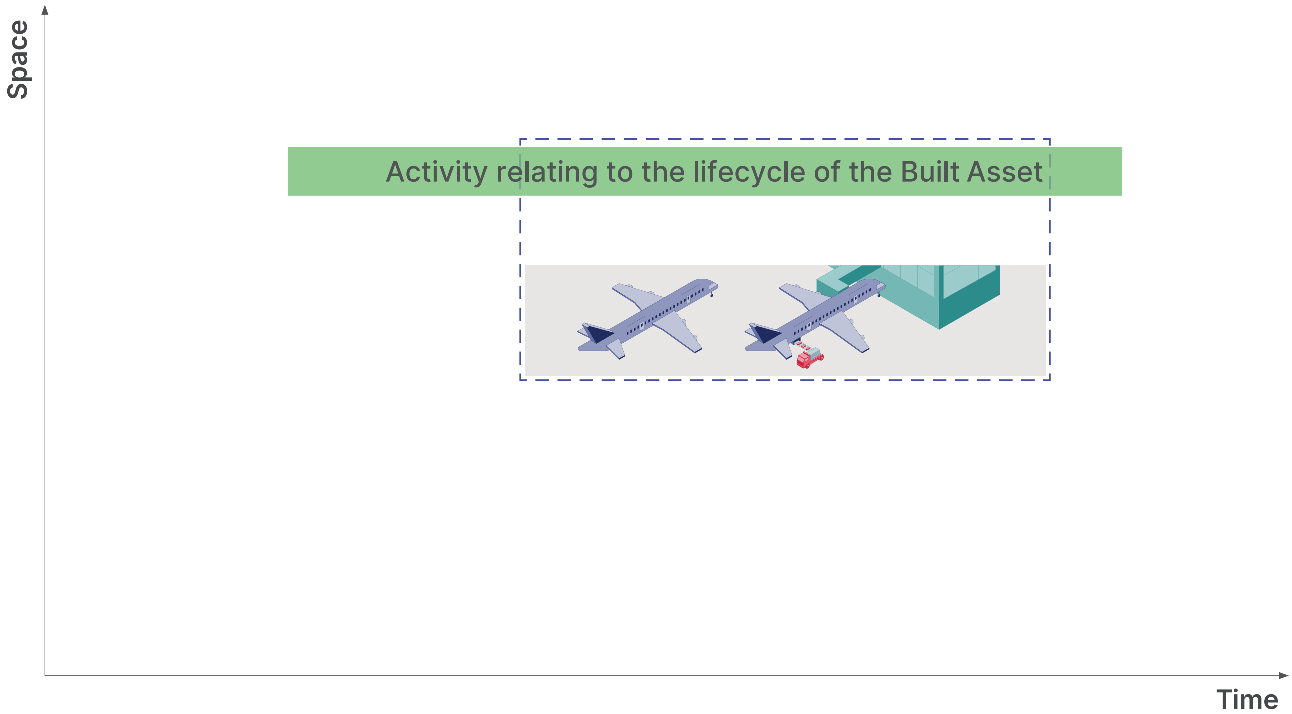

Figure 3: Activity relating to the lifecycle of the Built Asset

future activity that also needs those data. This leads to some key point for identifying information requirements:

- The need for information at the required quality can extend throughout the lifecycle of activity relating to a Built Asset System, and often beyond.
- It is more efficient to reuse information that was created, or obtained, earlier in the lifecycle of an activity rather that recreate it later to satisfy subsequent requirements for it.

The sort of activity that requires attention (by one or more organisation) in the management of a Built Asset system can be wideranging. The following list is just an illustration of the breadth of what can constitute such activity:

- Planning for the intended work at any stage in the Asset's lifecycle
- Concrete developing an initial set or hardened state after being laid on site
- Monitoring of natural ground subsidence that may affect all or part of the Built Asset system
- Design reviews
- A safety inspection of installed equipment
- Staff-conducted customer surveys
- A review of the use of parts of the Built Asset System
- Customer services such as transport, retail, communications, warehousing, allowed activities of their own choice
- Crime such as vandalism, assault and theft and how to deal with them
- Maintenance of a Heating Ventilation and Air Conditioning (HVAC) chiller plant or part of it
- The issuing of a tender for work to be done on part of the Built Asset System
- Handover of a commissioned Built Asset System (or part of it) to the Client/Client Representative
- Periodic inspection of food temperature in retail outlet refrigerators
- The updating of a plan based on reported progress and updated risks

It does not take long to realise that activity covers a lot; it certainly includes anything that may be done, planned to be done or happen that is relevant to the management of a Built Asset System. The particular activity that is relevant to a Built Asset System will be a function of the specifics of that system and, when the use of data is concerned, their analysis to determine the data requirements. If the system does not yet exist, for example as indicated in Figure 3, a lot of the formative activity may already have been conducted and the future performance of the airport will be reliant upon it.

A lot of attention can be paid to the design and engineering work that is both resource-intensive and a recipient of capital expenditure (indicated as the faded part of the airport preceding its being a functional system). However, even during the intense engineering work, it is a familiar disappointment to those involved in various parts of this lifecycle that the information that they need, and were often promised to enable their activity, was not available or was not as required. Again, through the analysis of the activity lifecycle there is a route to resolving these issues.

As we have picked a time before the airport exists as a system, it is useful to consider the role of information in the creation of the desired (example) airport and the activities involved. Figure 4 illustrates this by acknowledging that the future activity is just a possibility until it happens; often not quite as intended[3]. It is common to rely on plans for what is intended to happen and to create models of part(s) of the future airport but the task of managing all this planned activity, the representations of what we intend it to be and their reconciliation with what we believe has already happened can consume a huge resources. The oversight and management of the integration (including deconfliction) of these plans, the communication and reporting on them and adaptation to things that did not go as planned is significant.

An integrated approach to the use of data to inform these activities, including all the

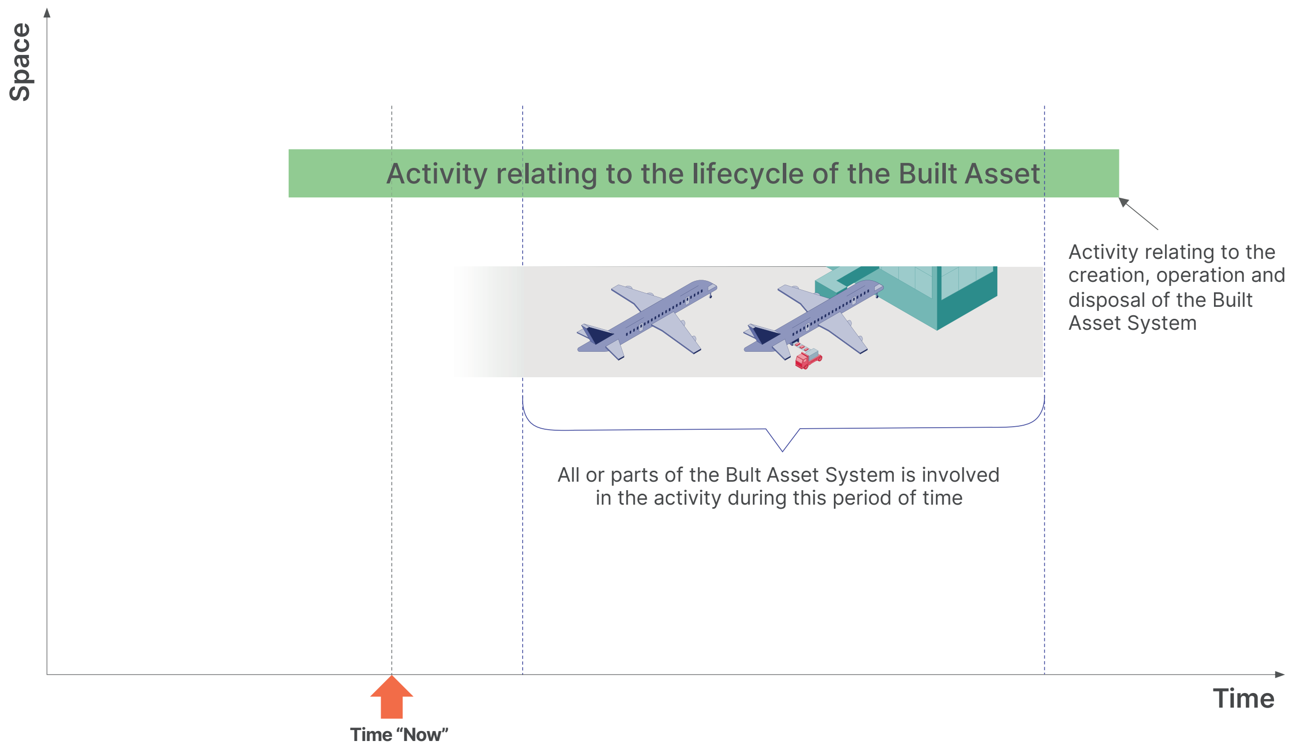

Figure 4: Development of the representation of Activity

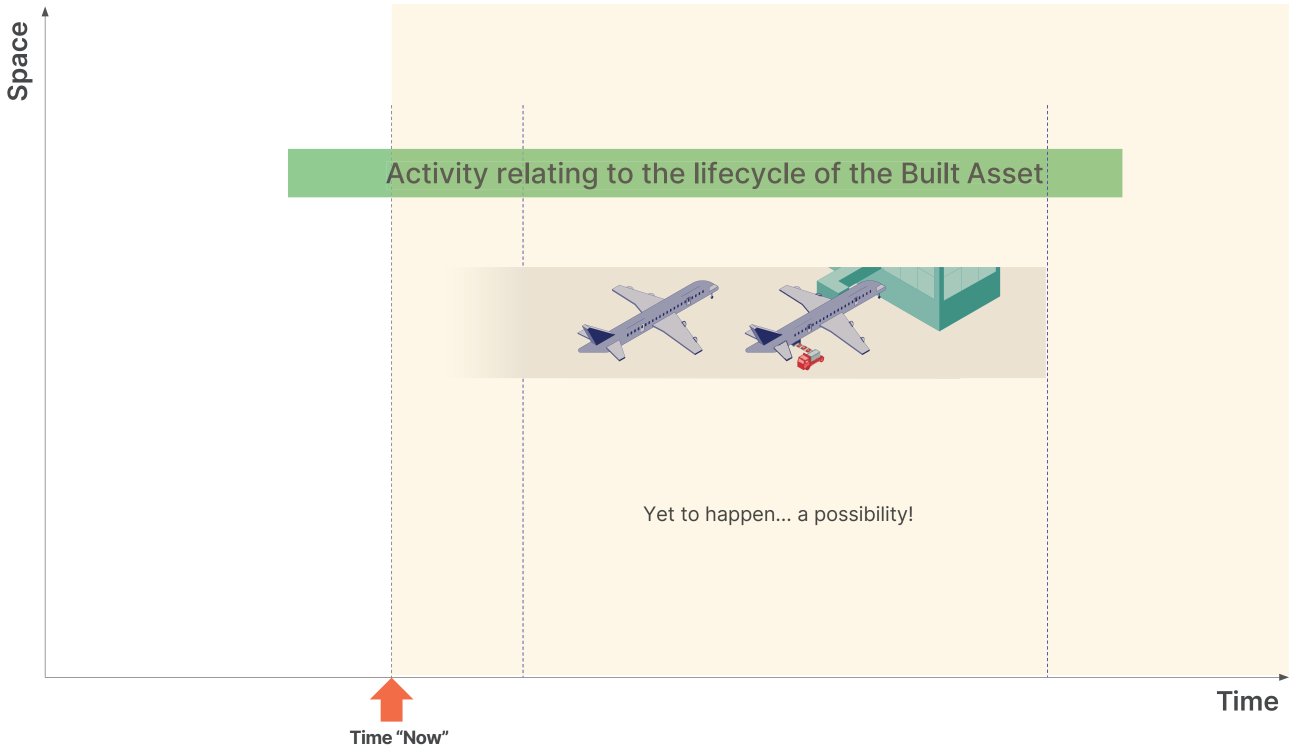

Figure 5: Dealing with the future

required things that are to be involved in them, is an area? / benefit? that the IMF enables and the foundation for doing this is integral to the FDM.

Since plans are representations of intended activity, they are of vital importance to the preparation for, management of and the resulting activity.

- Consistency in plans, the activity to manage them and the use of data to support them can be enabled through the use of the IMF.

A good insight to the use of an integrated approach to data modelling that could be mapped to the FDM is provided in (6). To end this section, it may be useful to reflect on the data that were created as a result of activity prior to Time "Now". Even if we apply the rigour required to ensure that the data are of the right quality (they meet an identified information requirement) it is still just a representation of a possibility of what really is. There is no magic thread binding the data to the objects[4] in the real world, even if we automate some of the work involved in keeping data records up-to-date. This will not be a problem for us if we keep it in mind that the data will meet our requirements but if it is part of a dataset that is labelled "Digital Twin", it is still just a possible representation of something that has a counterpart (twin) in the 'real' world (see (2) for more on this topic). If the data are not a good enough match for the counterpart, the process of information management has not worked as well as intended[5]. Checking for this once the data have been created can be costly. The cost of doing this is currently buried in the lifecycle activity of all of our national Built Asset Systems and constitutes wasted resource.

It is better to get a close match by securing advance capture of information requirements and meeting these from the outset. After this is done it is just a matter of maintaining it at the required level.

2.3 Activity in the context of Systems Engineering

Systems Engineering (SE) is an interdisciplinary approach that has evolved since the 1940s to address the lifecycle of large engineered systems (of any kind). As systems have become more interdependent, complex and dynamic SE is recognised as an important element in an increasing variety of systems.

A theme of this Chapter is that the lifecycle of a Built Asset System has an extent that involves activity from developing the concept for such an Asset to its disposal. Given the challenges associated with large-scale infrastructure developments, the Institution of Civil Engineers commissioned a report to investigate how "systems thinking can be used to improve the delivery of complex infrastructure projects". The following paragraph from the Foreword powerfully sums up their conclusions:

> "Systems, and not structures, provide the mobility, sanitation, energy and all other infrastructure services on which we rely. It is systems, not just structures, that we need to adapt if we are to decarbonise our economy. These systems are increasingly automated, interdependent and reliant on technology that is evolving rapidly. Yet many major infrastructure projects are still dominated by civil and structural engineering alone." (7)

The Systems Engineering community were one of the first to recognise that a lifecycle view of activity throughout the projects and programmes that they were involved with has considerable benefits. Organisations like INCOSE and standardisation initiatives such as ISO/IES/IEEE 15288 have created a foundation of lifecycle thinking applied to projects and programmes, such as commercial products, military systems, medicine development, space flight programmes at organisations like e.g. NASA. In the next Section reference is also made to the application of these systems engineering activity lifecycles to any large Built Asset System. One example that has already published a lifecycle model for large infrastructure developments is the U.S. Department of Transportation, Federal Highway Administration, California Division, in outlining the Systems Engineering approach to Smart Transportation Systems (STS) (8). This document provides a link for such domain initiatives with a generalised lifecycle process model for any Built Asset Systems and a path to the use of information at the right quality in infrastructure programmes like the STS example.

The Systems Engineering community recognise the reliance that their activities have on information (as data). In 2017 the INCOSE Requirements Working Group (RWG) presented a paper at the 27th Annual INCOSE International Symposium (9). The opening paragraph, quoted below, provides a complementary view of the role of information outlined in this document:

> "This paper was written from the perspective that requirements, along with all work products, models, designs, documents, diagrams, drawings, etc.) generated during the performance of System Engineering (SE) lifecycle process activities are represented by underlying data and information that must be linked together and integrated into a common, integrated dataset. Using this perspective, **the common, integrated dataset can be viewed as the foundation of Systems Engineering**." [bold reproduced from original paper, (9)]

The paper also states that fundamental to forming an "integrated dataset" is the definition and documentation of a "project ontology" and a "master schema" that is based on it. The RWG left the consideration of what a suitable ontology could be to projects themselves but this can be a hard set of choices to make once work has started, particularly when the goal of the selection is to "ensure consistent use of this information across all lifecycle stages", (9) Page 11.

The provision of the FDM, as part of an Information Management Framework, should therefore provide an attractive choice for the Systems Engineering community as it has been created to enable this goal for any application (especially Systems Engineering). The extensibility of the FDM should enable the Systems Engineering community to maximise consistency, ease the exchange of information with other disciplines and enable reuse of information throughout the lifecycle of their activities and with other lifecycles.

There is also a heavy reliance by the Systems Engineering community on Model Based Systems Engineering (MBSE). As systems become more complex, integrated and interdependent consistent representations of these models are desirable. Managing requirements of the models and checking for compliance/consistency are reliant on getting the representation of these models right in data. Again, this is where the use of the IMF with the FDM at its heart is something that should enable the use of data as a "foundation of Systems Engineering". It also provides a route to addressing what exists already (real, material things in addition to data on them) and the new, a common challenge that most systems engineering projects have to deal with.

The analytic approach introduced in this document is underpinned by ontological commitments in the FDM that ensure extensibility of the modelling, whatever the requirement. In (9) the selection of an ontology is left as an exercise for the Systems Engineering projects. Such a selection process is a non-trivial undertaking and the success of the project can be undermined by not choosing the ontology wisely, particularly where data consistency and information integration are needed. The IMF has embedded an ontology that is likely to meet the needs of all the data modelling requirements for all Systems Engineering undertakings[6].

A vision for Systems Engineering in the UK, at least for those involving Built Asset Systems, could be the adoption of and reliance on the IMF to foster the use of trusted, well managed information that is of the right quality.

3. Process Models – Prescriptions for Activity

As information is required to support decisions consideration should be given to when that information can and should be created (and its subsequent maintenance at the required quality). Often this information can be created early in the Built Asset System lifecycle, often during the design or other preimplementation activities that can precede the implementation of the system itself. If information created during these key activities is not recognised as needed at a later date and managed appropriately to allow it to be used with some efficiency, it will not be used productively weeks, months or years later. Ensuring that the role of information is addressed in a lifecycle sense needs a model of the interrelated activities that are intended to achieve an outcome and this is where process models are needed.

Activity models that are developed to meet the agreed needs of those involved and take account of the needs and experience of the industry/sector/related organisations can be generalised to form an outline process. In the cases covered in this document there is a common interest in the activity resulting in something (e.g. a state of a physical system or component being completely installed and accepted as installed and operating correctly). Identifying significant points in the activity lifecycle is essential to identifying information requirements because it is likely that there is something about the event at the end of the activity contributing to these points that is worth recording in data. It is also likely that there is a lot of data that may be needed for recording and even delivering (exchanging), but is likely and desirable that the information will have been required earlier in the activity lifecycle.

If information management is conducted well, the significant information exchanges should take little effort as the information required should be available and of the required quality – and therefore able to meet the goal of supporting decisions.

Although there is a myriad of lifecycle processes available for use in a range of industrial applications, very few are directly compatible with the activity analysis introduced in this document or the integrated management of information that should result from it. Not taking a consistent lifecycle view presents a barrier to information management and directly limits the analysis and meeting of information requirements. To illustrate the mapping of the Built Asset System Lifecycle Process Model to existing process models and standards a table is provided in the Appendix, Section 8.

3.1 Built Asset System Lifecycle Process Model

The first Chapter of this document introduced the activity lifecycle for a Built Asset System, using an airport as an example. It also emphasised that information required to support all of the activities that comprise the set of lifecycle activities can be required throughout it; data created early on in the design could be vital to operation and maintenance, or even during Asset disposal many decades later, even if the particular activities are very different. This section introduces a generalised, complete lifecycle process model that can be used as a basis for activity modelling, information requirements analysis and mapping to existing processes where appropriate.

A significant amount of activity takes place before a Built Asset System is built and commissioned (or an existing one undergoes an upgrade). This is often variously referred to as Design & Build, Architecture Engineering and Construction, Concept to Handover, etc. While a lot has been written about these nominal phases of the development during the lifecycle of a Built Asset, the role of information throughout them, and the interdependence of the activity and the information it requires, has not been addressed sufficiently to enable the integrated information management we now expect.

Figure 5 shows a space-time diagram, based on the previous examples, that partitions the activity lifecycle into a number of process stages. To be clear, this is a representation of the activity associated with the lifecycle of a 'complete', new, Built Asset System. However, the activity lifecycle for a major upgrade or addition to an existing system will likely follow the same pattern; ideally with information available from previous activity associated with the preexisting elements of the Built Asset System.

A key word that is used in this lifecycle process summary model is "implementation". It has been chosen to minimise an association with existing sector-specific process

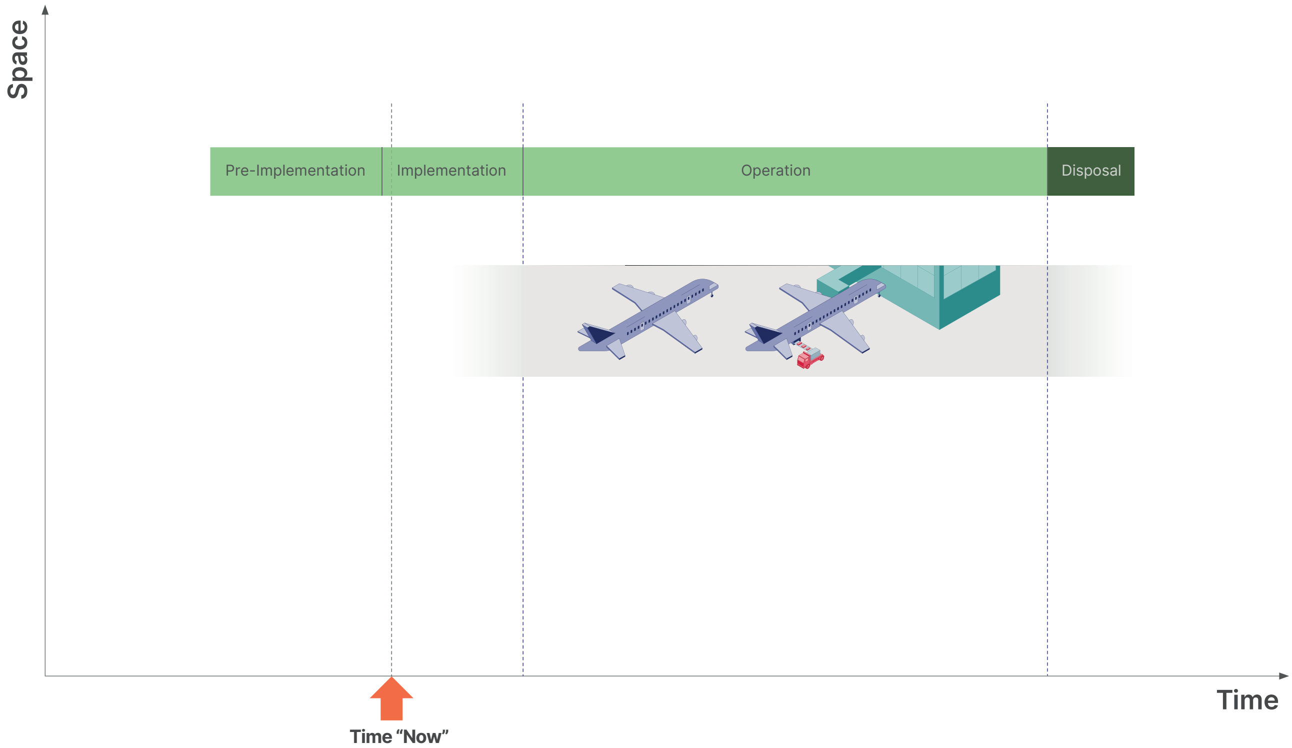

Figure 6: Generalised Lifecycle Process Model for large scale Built Assets

terms such as those listed in Section 8. In part this is to aid objective analysis of the activity, whatever the application domain, and to enable mappings to existing process models that may be required in sectors for contractual purposes or because they are established. After all, no Built Asset System exists in complete isolation from others.

Before providing a summary description of these generalised lifecycle stages a definition of the term "implementation" for our purposes is provided:

- Implementation: "the process of putting a decision or plan into effect; execution."[7] For the purposes of this lifecycle model "implementation" is the process of putting a planned activity to create an operational Built Asset System into effect.

Building on this the lifecycle stages are described in Table 1.

BAS Lifecycle Stage	Description	Example Activities
Pre-implementation	All coherent activity[8] relating to the Built Asset System that results in an agreed plan to implement all, or part, of a Built Asset System and a decision to enact that plan to create the physical Built Asset System.	Conceptual design, Feasibility Systems Engineering Architectural design Front End Engineering and Design (FEED)
Implementation	All activity involved in the process of putting a planned activity to create an operational Built Asset System into effect, to the point at which it is agreed to be Operational.	Engineering delivery Construction MEP[9] installation On-site assembly Material delivery Commissioning
Operation	The activity involved in the functional use of the system in a way that allows it to operate as intended. For most Built Asset Systems this will be the longest lifecycle Stage.	Service delivery Maintenance Support Operations Upgrades
Disposal	The managed retirement of a Built Asset System from Operation to an agreed end-state.	Reclamation Demolition Decommissioning

Table 1: Built Asset System Lifecycle Stage

For some Built Asset Systems, such as infrastructure megaprojects, the Preimplementation stage can last decades while a convincing and politically acceptable (and affordable) case is built. The Implementation stage is typically shorter but can encompass an intense period of high capital expenditure, risk and scrutiny. Any shortcoming in the quality of data from the Pre-implementation stage can have a major impact on the quality of work done at this Stage. The main product of the activities in this stage is information and so there is a direct link to the need for a comprehensive approach to data quality from the outset.

A lot of information can be created during the Preimplementation and Implementation Stages on the state of the assembled system and its components. If this information is required during the operation and maintenance of the system then ensuring that it is available, at the right quality, to those who need it at the later stage needs ongoing management of that information before, during and after its creation in the earlier stages. The Operation Stage is typically the longest, involving different organisations many years after the BAS has been brought into use, but use of data that is managed from earlier stages to be available to those who need it is the best way to support these later decisions. The role of information extends to the eventual retirement or repurposing of all or part of the system. Again, information created at all the earlier stages of the lifecycle may be essential to the appropriate and efficient end of life activity, and enable more effective recycling and lower energy footprint of this final stage.

If there has been insufficient analysis of the requirement for information, then by the time there is a need for that information it is likely to be below the required quality (or even not available at all). Neither situation is desirable. The lifecycle of information can also span built asset lifecycles (such as being able to use information on the previous uses of a site to address potential contamination). Enabling this becomes easier if it is addressed within / during? each Built Asset Lifecycle.

Upgrades, repurposing or decommissioning all or parts of a Built Asset System may need a full BAS activity lifecycle, depending on the scale or material change being made. In any case the lifecycle of these activities may follow an established Engineering or Systems Engineering Lifecycle (see 2.3) that occurs in the context of the Built Asset System Lifecycle.

A powerful statement from (10) that identifies lessons from the decommissioning of Nuclear Power Plants is also true of other infrastructure assets:

“Experience has shown that, in general, records for decommissioning purposes have been poorly managed or not managed at all. There are many reasons for this. Among these are:

- little understanding of the requirements of decommissioning, especially the need for
- accurate configuration drawings and plant data;
- a belief that, if all records of the facility are kept this will suffice;
- lack of well-defined responsibility for decommissioning records within the organisation;
- lack of priority being given to key records, such as those needed to sustain the operating safety case and for critical maintenance;
- after shutdown, the loss of interest in all records as operating staff is dispersed.”, P24

If we are to employ data throughout the lifecycle of our national assets and the activity that depends upon them, we have a lot to gain from avoiding, and taking remedial action to address, these shortcomings in the coming decades and centuries.

3.1.1 Built Asset System Activity Decision Support

The role of information throughout these lifecycle stages is predominantly for decision support. Analysing future decisions in later lifecycle stages and identifying information requirements early can allow information records of the right quality to be created, when it is most cost-effective to create them and, if managed appropriately, can avoid costly activity that later attempts to create information by surveying or inspecting in-use assets.

The role of information in decision support is critical to the management of the understanding of detail required at each stage. Existing process models can help with this. For example the INCOSE Systems Engineering Lifecycle Process Models (such as the "V-model") can provide guidance (11) & (3). Ref (3) uses the term "implementation" to refer to the activity at the base of the "V" and mapping it to the lifecycle activity model for a Built Asset System the activity to the left of the base of the "V" is pre-implementation.

A paper from 2018 emphasises the importance of integrated data to Systems Engineering, (12), and the INCOSE 2025 Vision[10] commits to supporting an "integrated engineering environment" that draws upon data integration.

The INCOSE "V-model" has been extended for application to large infrastructure projects by the U.S. Department of Transportation, Federal Highway Administration, (8) for application to Intelligent Transportation Systems (ITS). A mapping of this extended V-model is provided in Appendix 1. (8) also provides an activity breakdown for each lifecycle phase focussed at ITS and description of "decision gates" which illustrate some higher-level decision points in such large-scale developments and this is summarised in Section 8.

Many high-level process models overlook both the full extent of the Lifecycle Activity that is relevant to a particular Built Asset System and the role that information could and should have in that activity. Although we are largely considering activity that relates to intentional, planned human endeavour in the full lifecycle of a Built Asset System, information may also be required about things that already exist, such as the engineering geoproperties of the top 2m of the subsurface land for an infrastructure development or the interfacing to and capabilities of utility supplies for such a development. The analysis is equally important in these circumstances as it will allow the specification of what information is needed from other service providers to be made clearly and allow information quality gaps to be determined early where existing records are expected to be used.

Another vital part of involving information in the support of decisions is the need to identify the requirements for the information that is sufficient to making sufficiently 'good' decisions. The first time some information is needed it is likely to be a relatively detailed, even low-level activity. Subsequent detailed or higher-level decisions that require the same information will depend on the quality of these existing data and may even require the set to be of a higher quality (regulatory requests for information or compliance records are an example of this). The message from this observation is that the activity of determining and agreeing information requirements needs to work for any required detail.

While attention is often devoted to the higher-level decisions (and data exchange points) in the lifecycle process models for Built Asset Systems they become a lot easier to address if the information requirements for all the supporting component activity are of sufficient quality. Higher-level decisions that require summary information (and related data hand-over or exchanges) can then become a relatively simple matter of processing the existing information.

The next subsection explores an activity model concerning any Built Asset System that involves Engineering Activity.

3.1.2 Built Asset System Engineering Activity Model

This section draws upon work originally conducted in the 1990s by the Process Industries, in particular the Process Industries STEP Consortium, to capture the lifecycle activities of large built facilities such as Oil Refineries, Gas Processing Plants and Petrochemical Facilities. In 1994 they published an Engineering Activity Model (13). In turn it was incorporated in the outline for the standard ISO 15926-1:2004 (14) for the integration of lifecycle data throughout such process plants. In addition to providing a generalised activity model broken down to several compatible levels of detail it also illustrated significant points of "data flows". A similar approach is adopted in this section to introduce an Engineering Activity Model (EAM) for a BAS. It provides a lifecycle view of the Enterprise activity involved in the engineering lifecycle of a BAS. Figure 6 shows the scope of activity covered in the rest of this section and it illustrates the context in which typical "engineering" activity takes place.

Figure 7: Business Activity scope for the Built Asset System Engineering Activity Model

Before adding some detail to these activity areas the following list provides a brief introduction to each:

- Supervisory Management Activity: This is the oversight of the other activity, ensuring that funding is available, targets are met, progress is suitable and that risks are in-hand. It includes management to meet business case objectives and r egulatory or policy requirements.
- Service Activity: From professional services to those that provide specialist and skilled resource early on in the lifecycle to ensure that the resulting system is able to function as needed. This will enable the provision of the services that ultimately rely on the built asset system and the needs of the organisations that rely on it.
- Engineering Activity: The design, development, physical creation and construction, analysis and performance improvement of the Built Asset System to meet the requirements of the client organisation(s) and the services that they wish to offer. For most Built Asset Systems the bulk of the Engineering Activity is needed prior to its operation. This resource intensive activity will depend on information and will create much of the information needed later in the lifecycle and by other activity areas. Engineering Activity includes maintenance and upgrades while in-use and ultimately any dissassembly or repurposing many decades later.
- External Supply Activity: The engagement with suppliers of products and services to supply cost-effective and compliant solutions when required.

The previous figure has been expanded in Figure 7 to illustrate the information flows that will take place to ensure that these groups of activity are sufficiently integrated (and informed). While the general message is that information exchange will be needed between these activity areas, a key point is that an integrated approach must work at all required levels of detail, not just the summary. This is a vital message. If it does not work at a sufficient level of detail, then it is false to claim that a summary view is all that is needed to implement what is needed.

In a similar style to (13) this can be 'projected' onto the Built Asset System lifecycle process model. Figures 8 & 9 illustrate this, indicating the sorts of activity that can be expected at each stage. Figure 8 shows how the BAS lifecycle process model can be mapped to each activity group. Figure 9 builds on this with an indicative list of activities that are associated with the mapping. It is not a substitute for activity analysis for a particular BAS but it illustrates the kinds of activity that will be needed in most BAS activity lifecycles. Figure 8 also indicates in yellow some principal information management activity associated with each stage and activity group. The information lifecycle will start with analysis during the preimplementation Stage to derive information requirements for it and the subsequent stages. The information management should be continuous throughout the BAS lifecycle and, since the goal of the activity analysis is the identification of information requirements of the required quality, there is no avoiding that information management is embedded in the lifecycle activity too.

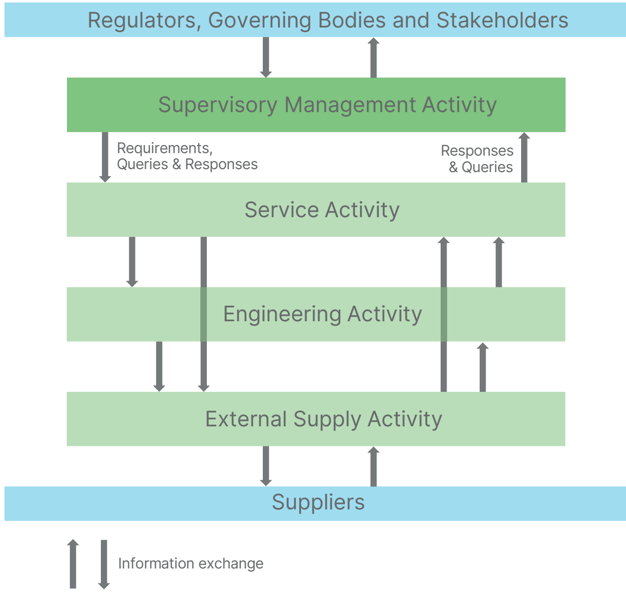

Figure 8: Information exchanges between activity

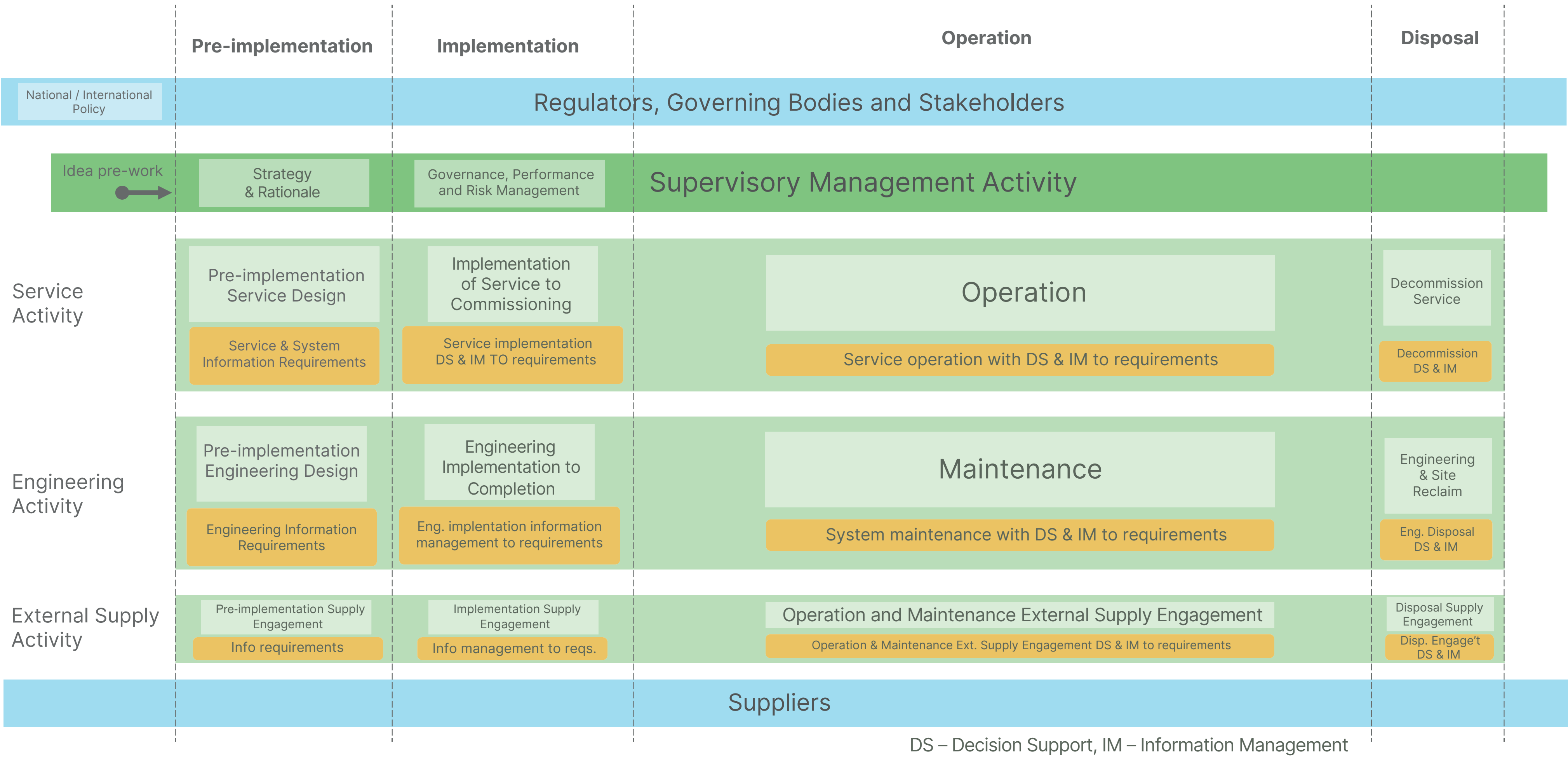

Figure 9: Mapping of Built Asset System engineering activity scope to the process model

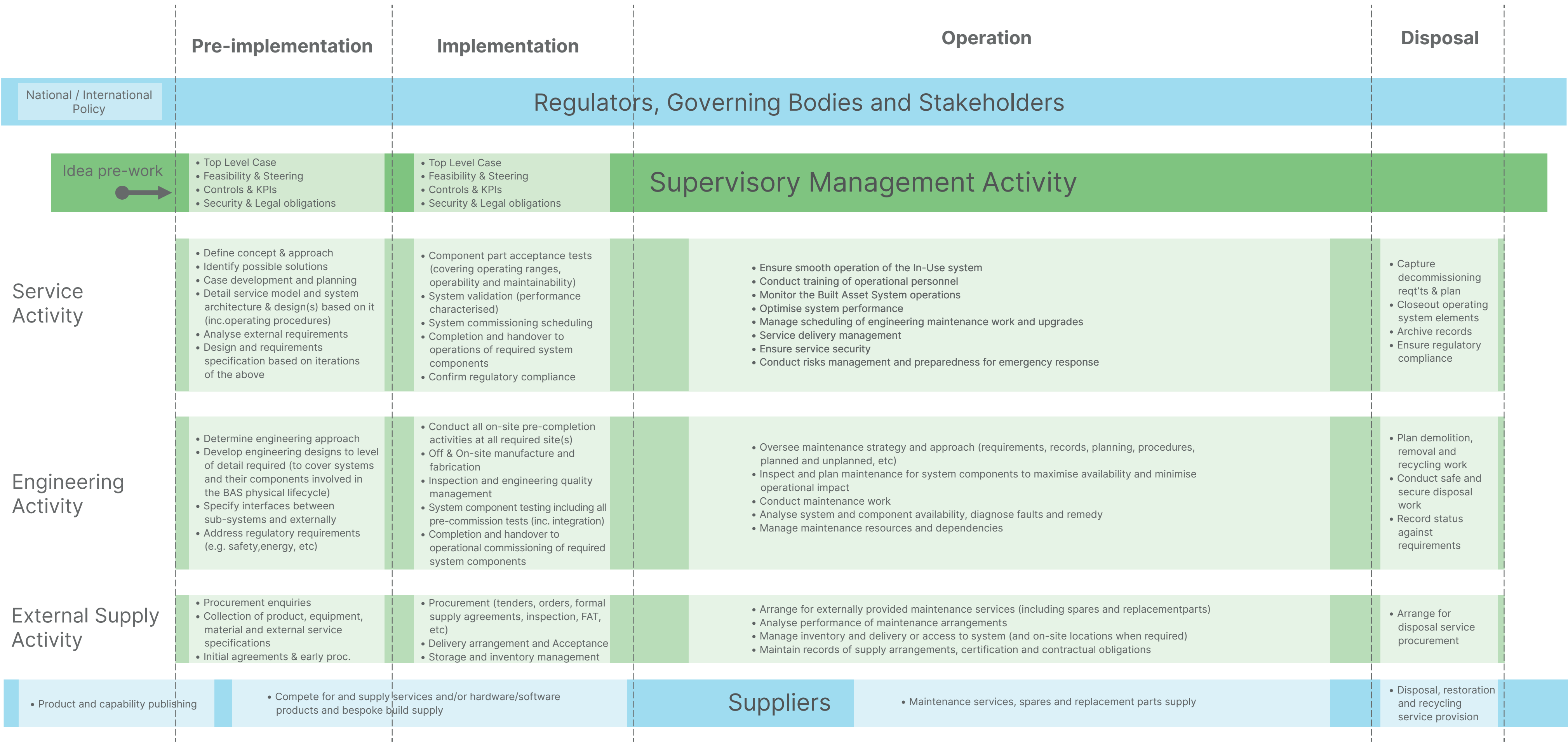

Figure 10: Indicative activity lists for the parts of the Built Asset System Engineering Activity Model

3.1.3 High-level Information exchange points

It is tempting to introduce illustrations of information exchange to the diagrams already provided in this section. However, this can be misleading as it is a distraction to think about those possible information exchanges without devoting sufficient closes attention to the preceding activities . It is the detailed activity that requires particular information and results in new information. Any requirement to hand over information at a higher level (such as the handover from commissioning and accepting a system to running it to provide full operational service) should really be a matter of collecting already generated information that meets the agreed requirements. As stated earlier, if there is a requirement for specific information to be made available during the later operation phase of a system's lifecycle, then that should have been identified during information requirements analysis earlier in the lifecycle and be available for inclusion in the information delivery at a Handover event.

Of course, it is unlikely that all the information required at a later Stage can be identified and created at a point that is most cost-effective for its creation and management – this would require complete knowledge of the future. Equally, much of what will be required can be identified well in advance of its being needed. If the information is managed in an integrated manner, it will increasingly be an exception that information is not identified and created in advance and, when it is not, can be created and integrated with existing data to satisfy subsequent requirements for those data. A cost-effective approach to data requirements and information management should be adopted throughout, with a goal of capturing information requirements as soon as they are identified and as early in the lifecycle of the BAS as is practical. The expectation should reasonably be that most if not all of the information can be identified and created in advance.

3.2 Periodic Operational Lifecycle Model for an Organisation

Organisations, particularly those that are large and have a corporate or public service structure, tend to have activity that is dominated by periodic decisions. These may often be annual (e.g. financial year obligations, budget allocation etc), periodic within years (monthly sales reviews, quarterly progress decisions, etc.) or longer (strategy reviews every 5 years, etc.). Much of the activity in the organisation centres on such decisions or is dependent upon them. This is illustrated in Figure 10.

Other activities, with their own identifiable lifecycles (production runs, R&D, service delivery, marketing, finance, etc.), may take place to support this top-level periodic lifecycle activity. Each will have its own information requirements and may be required to supply information that directly supports the top level. There may also be a requirement to keep track of other lifecycle activity such as that of capital investment in Built Asset Systems. This is illustrated in Figure 11.

The figure uses a school for illustrative purposes. To develop this further, extracts from the Institute of School Business Leadership Toolkit, ISBL, (15) are used to illustrate the activity cycles present in the UK school calendar that are vital to the annual operation of a school. As mentioned in Section 2.2, these periodic processes are intended to support the Core Processes of the organisation. For this education example the core process could be the delivery lifecycle of secondary school education from entry at the first year to leaving at the end of the most senior year.

The Toolkit helpfully groups activity descriptions in a way that is similar to the approach taken for the PPEAM Engineering Activity Model:

- Leading Support Services: Strategic direction, school, system and trust level leadership, policy, procedure and process work, Health,

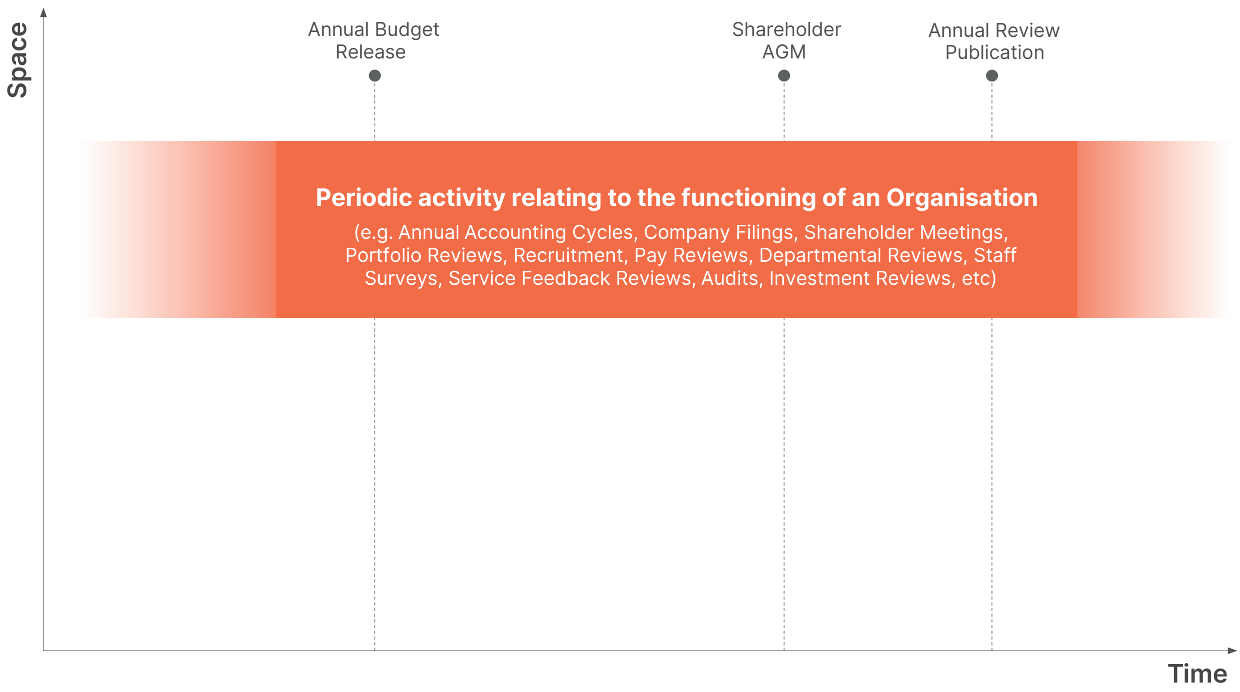

Figure 11: Periodic lifecycle activity of a large organisation

Safety & Risk, Safeguarding, Professional Values and Ethics, Continuous Processional Development

- Finance:
  Manage school/trust finances, oversee the business & finance decisions, promote good finance management, efficiency and effectiveness.
- Procurement:
  Procurement strategy, benchmarking, tender management, supplier relationship management, exit and closedown, compliance with statutory frameworks
- Infrastructure
  Asset management, Space planning (including occupancy surveys and reconfiguration options), Capital Planning and project management, Facilities Management, Grounds Maintenance, ICT
- Human Resources:
  School/trust design, Workforce Planning, Performance Management, Human Resources Management
- Marketing:
  Brand management, Communications and promotions, Income generation

Although Figure 12 just represents a selection of the tasks in the ISBL toolkit, they all have some setting with an annual or monthly cycle. These durations are just different time constants for similar activity patterns. They will be conducted in the context of the Core Process of the academy school, the educational lifecycle of secondary school pupils from starting at the school to leaving, as mentioned in Section 2.2. From the listed activity descriptions it can be seen that even at the top level there will be requirements to have information on the capacity, spaces, reconfigurability options and efficiency of the Built Asset System that comprises the physical school itself.

Further analysis would be required to identify how the activities indicated fit with other organisational activities, some of which may also be periodic, such as the teaching terms, the syllabus (for subjects

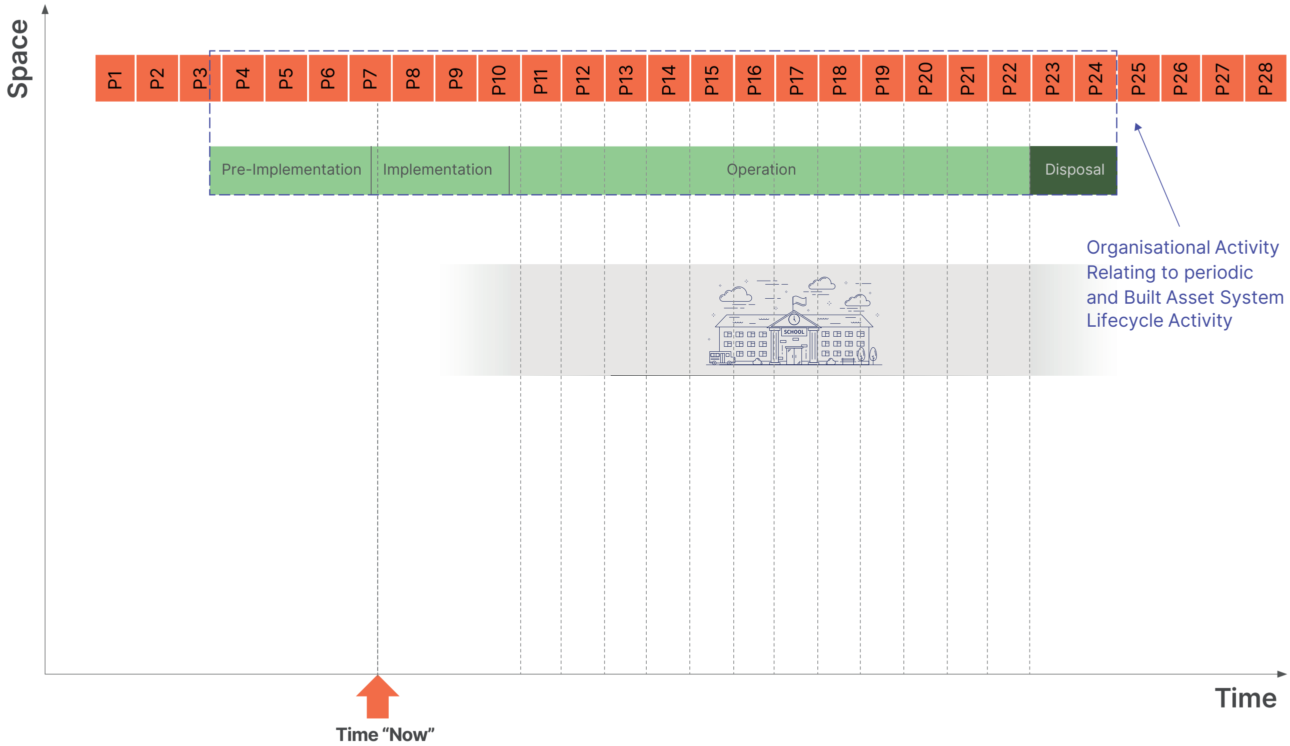

Figure 12: Simplified view of the lifecycle activity of a Built Asset System and the periodic activity of the organisation

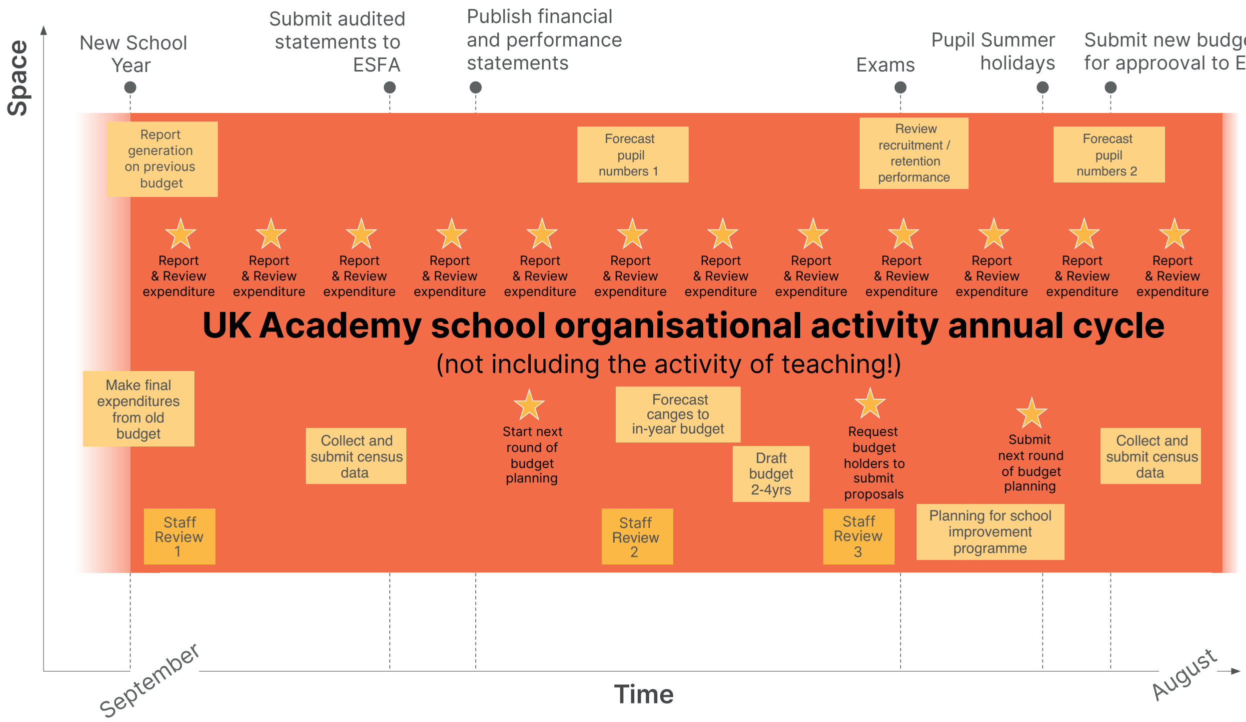

Figure 13: The outline activity for the creation of a brick wall at a school

taught) and the examination timetables. As all of these periodic processes support the organisation's Core Processes they will have information requirements of each other. Risk management and adapting to events (e.g. an injection of new funding, regulated changes to GCE[11] qualifications, dynamic adjustments due to flooding or a pandemic, etc.) can be more easily achieved if there is better information available on both the periodic and non-periodic activities (both planned and unplanned).

4. A closer look at Activity

In the introduction to "activity" in Section 2 we noted the importance of making good decisions as vital to activities that we care about. This is certainly true of most formal activities concerning the lifecycle of Built Asset Systems. It was also observed that information required can be created in advance of its being required for use, even by many decades for some information. Addressing this in a consistent and well managed manner so that the information can be used when needed is the function of a rigorous approach to identifying the information requirements. These, in turn, can only be known to a reasonable level of confidence by analysing the lifecycle activities to identify the decisions and the information required to support them.

To show how activity analysis can be performed this Section takes a closer look at a particular Activity, what is involved in it and why parts of it may benefit from the use of information. This worked example is not intended to be an off-the-shelf solution to the application area used in the example. Further analysis would be required to address aspects that are not covered here or are omitted for brevity. However, the example provides some of the essential aspects of analysing an activity, identifying decisions and the role that information can play in ensuring that the activity can take place in a manner that meets the project requirements. This section ends with an overview of the basic patterns that are useful any activity analysis and summarises the method illustrated by the example (4.5).

Identifying Decisions

Without analysis of the intended activity in an activity lifecycle context there will be an incomplete picture of the decisions involved. It reveals the activities that can provide the information required for the decisions throughout the lifecycle. This is illustrated by an example set of activities.

4.1 An example task – building a brick wall

This topical example should be familiar but, as the summary of the analysis shows, it can prove to be a fairly complex undertaking – although once done it should result in knowledge of what the data requirements are and provide a foundation for similar analysis for other, similar activity analysis. Although bricklaying is a common activity in the construction sector, there have been some recent examples where the quality of the resulting walls has been compromised to the point at which some walls at Edinburgh schools and Council properties failed once the schools and other buildings were in use (16). These issues are well documented and occurred in the few years prior to the Grenfell Tower tragedy in 2017. A formal review of the failings was conducted that resulted in 19 buildings' having compromised

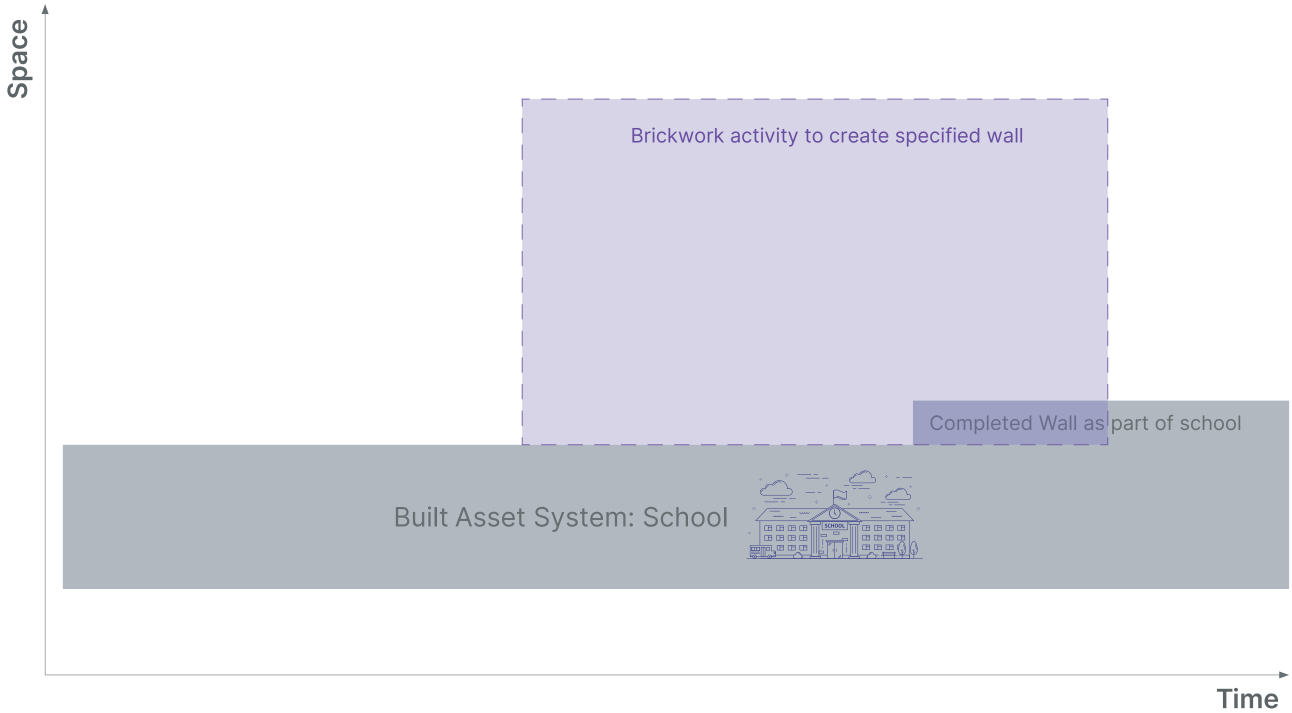

Figure 14: The outline activity for the creation of a brick wall at a school

brick walls and the results are publicly available (17).

What does an activity to conduct the bricklaying of a new wall to completion of the wall involve? An example scenario of a new brick wall at a school is used to perform some analysis. Figure 13 shows a Space-Time diagram showing the school that might be existing or new. The activity resulting in a new brick wall as part of the school is shown in purple.

From the definition of "Activity" given at the start of this study it is clear that an activity requires participants who have a role to perform. This is the case whether they are declared or not but it is the goal of this analysis to identify those that are relevant to the example task. These participants are not (yet) shown in the Figure but if it is a significant wall &/or part of a new school building programme, then it will be in the Implementation phase of the lifecycle of that Built Asset System Lifecycle, at least for that part of the Built Asset System. For now we shall focus only on the activity of the creation of the wall. However, a wall-building activity itself will have a lifecycle and perhaps be based on a standard (or industry norm) that outlines how to approach such an activity[12].

A simple sequence of tasks for the building of the wall is given in Figure 14, with the construction of the wall also bounded in purple. This diagram is used here to illustrate a nominal sequence of actions that building will follow to prime the rest of this section.

This task lifecycle can be mapped to the Built Asset System lifecycle process model even though it may be a very small part

Figure 15: Nominal outline process for implementing the example Brick Wall

of the entire set of actions involved in the creation and implementation of the system. For large Built Asset Systems this task may be one of many thousands and it may be one of the less complex. However, the analytic approach can be applied to any activity and even the analysis of the activity of building a brick wall shows that it depends on a lot more than one would generally expect without conducting such analysis[13]. In projects that have many such activities or where there are other process steps, such as agreeing a set of tasks and outsourcing or planning for them to be conducted together, it may be that these process stages are not contiguous (e.g. the specification of the task may be set well in advance of obtaining resources or some of the resources may wait in storge, or on site, until they are needed).

4.2 Identifying what's involved

We can start to identify the primary participants of the activity, as illustrated in Figure 15. Even without further inspection it can be seen that there are quite a few resources required in the activity under analysis and they all exist prior to the commencement of the implementation of the task (this is unsurprising but is easy to overlook).

How can we be sure that the required resources are available? This is where the lifecycle view helps us to identify what is needed well in advance. However, further analysis of the intended implementation activity can also reveal additional (and in this case new) activity. An example drawn from the Report of the Review Panel on Building Standards Compliance and Enforcement (17) identified that work (in particular brickwork) had been conducted as specified and was compliant.. The report recommended that Local Authority verifiers (similar to building inspectors) be required to be involved to check that the work done was compliant

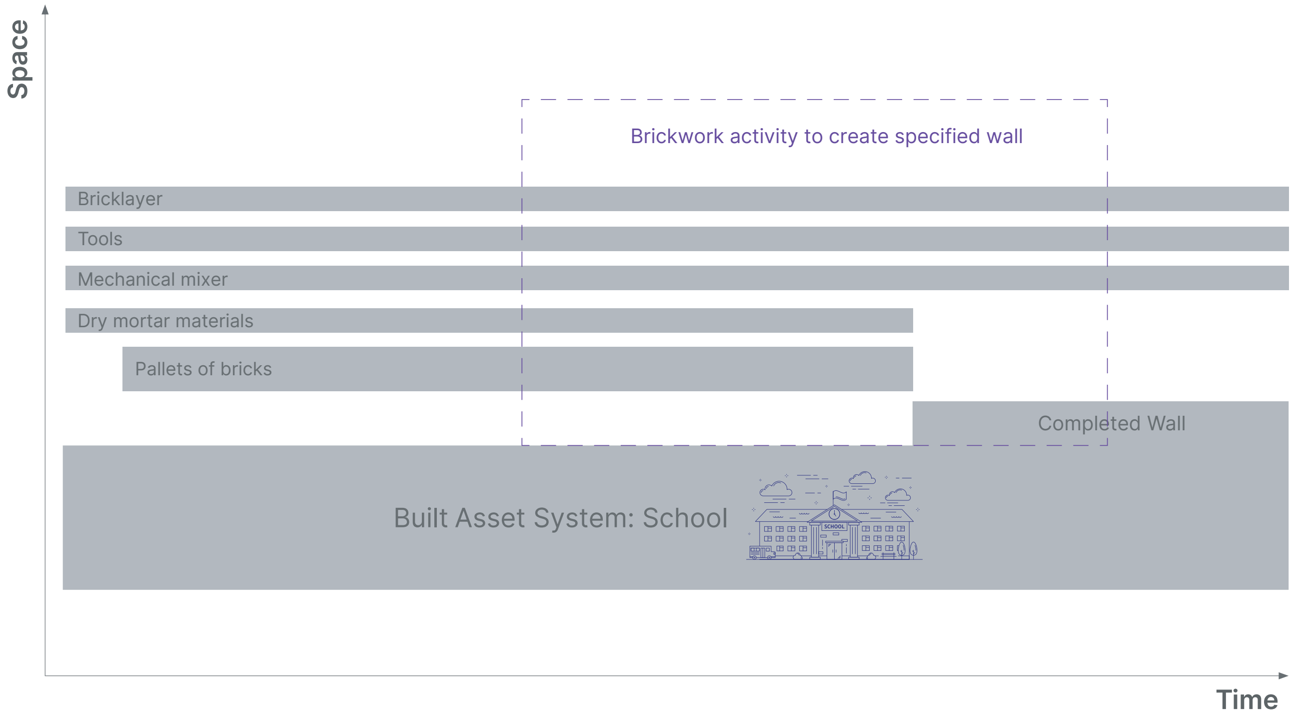

Figure 16: Identified participants required for the implementation of a brick wall

(and to be empowered to demand that identified defects were remedied).

"The role of the Local Authority verifier can be encapsulated into the following:

- **Approval of designs submitted with building warrant applications**.
- Undertaking site inspections during construction works.
- **Acceptance of completion certificates prior to building occupation and use.**
- Enforcement of parts of the legislation dealing with dangerous and defective buildings.
- Enforcement where contraventions of the legislation occur." (17), Report Page 11

This demonstrates that while the acceptance of the brickwork is dependent on verification towards the end of the task, that activity (and the entire wall implementation) is dependent on a previous activity; that of obtaining a Building Warrant[14] well in advance of initiating the work. We can now add these two identified activities to the space-time diagram, Figure 16. The two activities added that involve a Local Authority verifier can also be easily identified as requiring information and resulting in information:

1. Building Warrant Approval[15]

   Input information: This can require the submission of Technical Submission Plans, Site Location information, Site Plan, Documents covering regulatory requirements, etc. and any relevant Certification information. The approval process is intended to ensure that the design is compliant with national and local requirements prior to work's starting.

   Output information: Building Warrant

2. Verification and Certificate

   Input information: The warranted information used for Building Warrant Approval, an as-built pack of information and confirmation that the site is ready for inspection.

   Output information: This is determined,

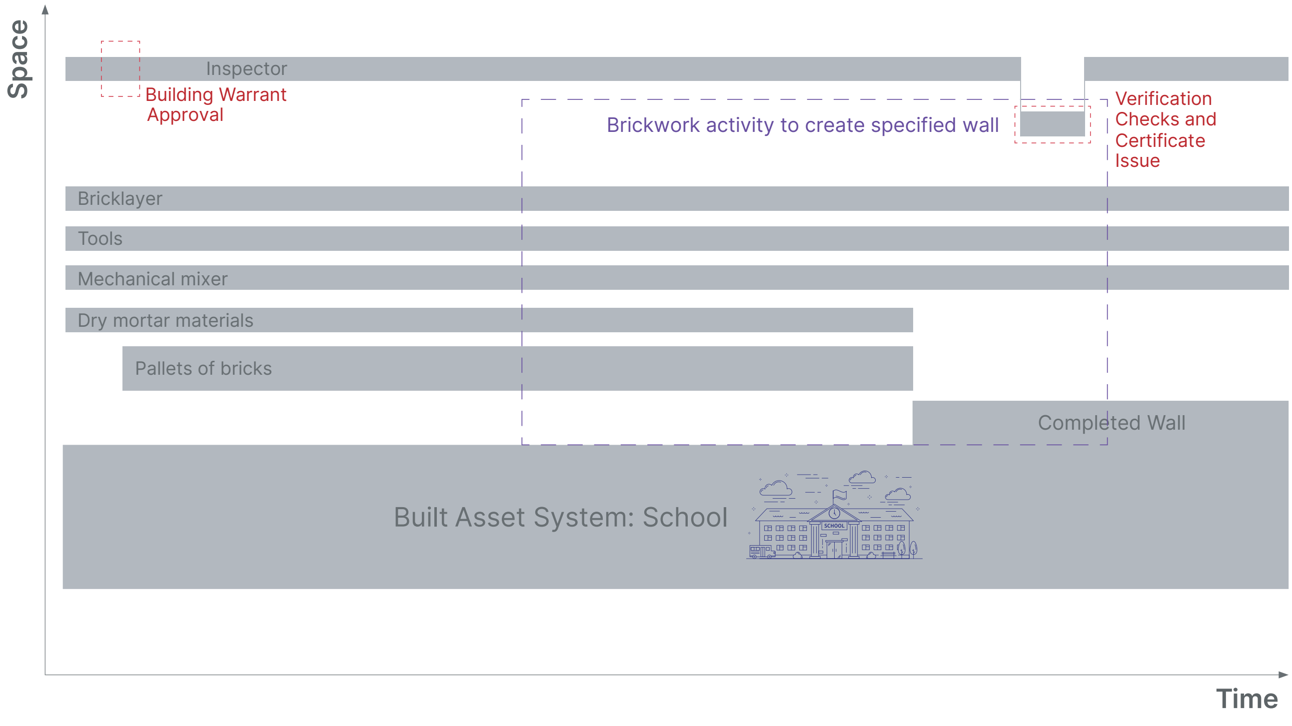

Figure 17: Addition of identified activity

often by a specified process, by whether the inspector has found any defect that needs to be remedied. Further activity may be required to allow the verification to conclude with a certificate of compliance. A record of compliance will be issued as a certificate.

The information likely to be required for two activities illustrated in Figure 16 is often supplied in electronic form but comprises PDF documents etc. The goal of the IMF is to enable this information to be represented in a structured form that is of the right quality to ensure that it can be queried and checked in an efficient, automated (or semi-automated) manner. Further iterative analysis and decomposition of the component participants to the required level can now be performed in an iterative manner.

4.3 Expanding each participant

We can now analyse each identified participant in the brickwork task and determine earlier lifecycle activities for each that is relevant (and required) for its successful implementation. This is a key point in the activity modelling work; each material participant involved has a lifecycle (the ontological commitments of the FDM are founded on this). Each can be analysed in whatever detail is required to identify dependencies (e.g. the need for other activity involving it prior to or after the activity that initially identified the need for it as a participant). This approach can add rigour to the design and planning (activity for) of Built Asset Systems and it is vital to identifying the information required in all activity that involved that material thing (e.g. building materials, equipment, people, organisations are all examples of such material things) as a participant.

Figure 17 shows some additional activity that can readily be identified as relevant successful implementation.

This example analysis will not go through each of the illustrated activities in detail, but some points may be developed by looking at a few:

Good knowledge is also key

Rigorous analysis requires good knowledge of what is being analysed. Hopefully, you will have started to think that there may be aspects of this example brick wall that differ from engineering, procurement, supervisory, etc activities that you have been involved with. That's a good sign that you can engage with analysis of activity analysis in your areas.

- *Design and Specification:* This activity is a key dependency for all the illustrated activities but it does not involve any of the identified participants of the Brickwork task. This is no surprise but illustrates the requirement for information to be available on all activities in the lifecycle of the Built Asset System. In many large infrastructure projects the design and specification, although Engineering Activity, can take place years before the task needs to be implemented.
- *Bricklayer:* A suitably competent person or persons must be identified in advance of bricklaying. The activity for the selection may vary with the scale of the task, any outsourcing model in use and particular certifications or skills needed. The person(s) must then be able to be present on site for the start of the implementation task.
- *Pallets of bricks*: These must be sourced, at the required specification and for a suitable cost, with terms for their delivery to site (an example of External Supply Activity from the BAS Engineering activity Model). Each of these activities will have specific requirements that may have regulatory, contractual or health & safety implications. Bricks can get manufactured individually in batch processes and then packaged up into suitable collections (for example, stacked onto standard pallet carriers and wrapped). It may be a requirement to have a record of the

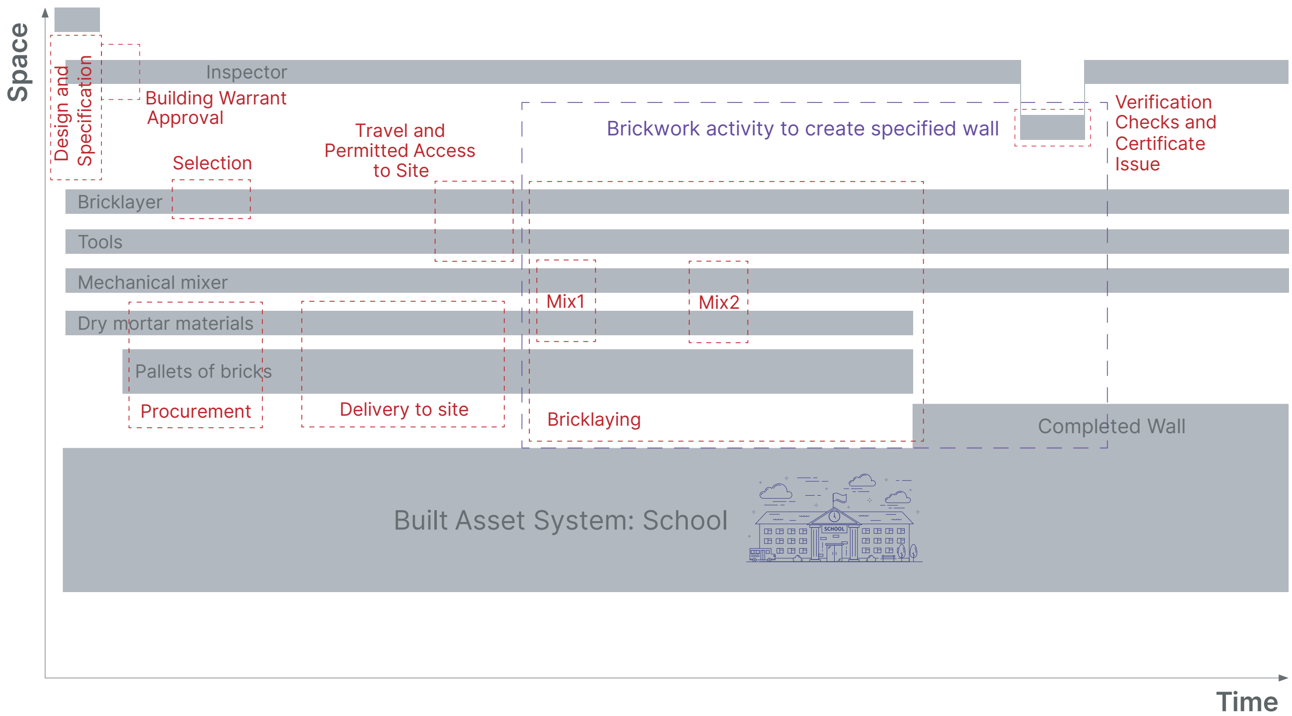

Figure 18: Further activity identification

material properties of specific batches of bricks and track their transit to site for monitoring purposes.

We can see already that there is a rich set* of activities* even for this example on which the brickwork implementation is dependent, and each will involve decisions and can require information created from earlier activity. Each activity will require information to result in the intended wall, information that is identifiable from analysis like this. From this initial level of analysis it can be seen that the identified activities (the dashed red boxes) can be mapped to the BAS engineering activity lifecycle model (Figure 9). Even on small projects this can be useful as different teams, disciplines and organisations can be involved in the activity groups (e.g. Engineering Activities can be undertaken by different individuals from Service, Procurement and Supervisory Activities). Further analysis of this example will reveal additional activity and information that is required. One area is that of supervision of the brickwork (activity) and

Mapping back to the EAM

Mapping the identified activities back to the Built Asset System engineering activity lifecycle model can be used to integrate component activities (like this brick wall example) with the wider system of activities that constitute the whole BAS lifecycle. This directly supports the goal of improved system outcomes and better integrated system engineering ( ).

management and coordination with other construction site activities. These can be addressed by applying the same analysis method to extend what has been illustrated here. A non-exhaustive list of considerations that may require further activity has been obtained from (18) to illustrate how the analysis could proceed:

Consideration	Description
Standards	Standards such as BS EN 771-1: Specification for masonry units or NHBC Standards may apply and require specific things to be addressed.
Types and forms of bricks	The specification of the bricks and require detailed discussion with manufacturers to ensure that they can be supplied (or to understand any compromise incorporated into the eventual requirement specification).
Reference / sample material	Does there need to be an advance activity involving a small reference build with representative materials, perhaps for approval as part of planning conditions?
Assurance of supply	Are additional measures required to ensure that the sourcing is known and that there is evidence of the supply of compliant materials?
Protection	Do the bricks need special protection, before, during and after the brickwork activity?
Mortar specification	Are there any special requirements of the mortar, any additives, its storage and handling on site? What are the setting times? Is there a maximum height for new layers of bricks that can be added to the wall in a day?
Co-ordinating sizes	Do the requirements state the need for adherence to specific bonds, mortar depth and application?
Site cleanliness	Do materials during work need to kept from surroundings that may be damaged or impacted by them?
Weather	Are there specific requirements on the environmental conditions for the work (e.g. temperature >3degC, protection from rain while setting, etc)?
Health & Safety	Are new risk assessments required? Are any specific measures needed to protect those doing the work (e.g. working at height, mixing dry mortar may need masks, etc)
Supervision	Is specific supervision required (e.g. supervision may be outsourced but evidence of it required, security escorts may be needed, etc)? A bricklayer supervisor may be required to manage a team of bricklayers to do this and other activities. Site management and coordination of these and other activities will likely require supervision and reporting for decisions relating to the wider BAS lifecycle activities.
Additional materials	Additional items such as clean water and an area to safely clean work items and dispose of unused mortar may be needed.

Table 2: List of additional considerations that may identify additional activity in an extended analysis

Can we identify everything needed to be involved in this initially simple-sounding brickwork activity? This is where analytic rigour, judgement and active quality management is needed. A simple example is the need to have water available that will be required to mix the mortar. In some cases it may be trivial to obtain the water but for some large or specialised tasks it may be necessary to address the precise need for water (e.g. sourcing, quality, on-site storage, quantity measurement, etc.).

As the goal is to identify decisions that require information it is the analysis of the activities (represented in our example by the red and purple bounding boxes) that will reveal the information required to allow the activity to start or that is created during/after it to support subsequent decisions.

A useful discipline is to try to extend the analysis to one level of detail beyond which there is a requirement to go. This helps positively to confirm when activity does not need particular attention, or data, and ensures that requirements for data are less likely to be overlooked. It is less expensive to analyse activity in advance than suffer the cost, or other consequences, of its going wrong as it takes place. This analysis approach can also complement risk analysis. Most activity does not happen at zero risk. Risk management itself is activity too and can and should be factored in to the analysis.

4.4 Bringing it all together

Consolidating the analysis of the brickwork implementation is now a straightforward task. The information requirements for the task are composed of the decision-support information resulting from the previously identified activity and the information produced as an output (as it will be required for decisions in subsequent activity – if not, there is no need to produce it).

Integrating all this into the activity models and information requirements for the wider lifecycle activity for the rest of the Built Asset System is a task of aggregation with the equivalent outputs of the other activity analysis. This does not mean that the BAS information or the requirement for it are aggregated into a single system or managed together (this may be counter to the data quality requirements identified, such as the need to protect some of the information for commercial or other securityreasons) but it does mean that there is a consistent basis from which to assess, plan and manage all of the identified information as needed.

The results of analysis like this can significantly reduce the work involved in the following areas:

a. Information Requirements & Information Management
The analysis should identify what information is needed, by whom, when and at what level of detail and/or quality. If performed appropriately it will result in information requirements that are expressed in a way that result in data of the required quality as the activity is undertaken and, if good information management is applied, ensure that the information is available when needed at any subsequent point. The activity of information management throughout the BAS lifecycle will depend on the quality of the work done to identify the information required wherever and whenever that is.

b. Planning
Activity modelling is not planning (see earlier definitions). However, the quality of plans as “specifications of possible activity or series of activities” can benefit directly from the activity analysis. This can be modelled using a suitable data model in a way that facilitates creating and managing plans, and checking for consistency with what is intended through the resulting real-world activities that are conducted.

c. Re-use and extension
While copying activity from a previous analysis sounds like a good idea, it is a recipe for overlooking things that differ in a particular activity. However, using previous analysis as a guide can greatly improve the efficiency of subsequent analysis. In

addition, if requirements are subsequently changed (for example more information is required on one or more participants),then the analytic rigour can allow a natural extension of the analysis to address what is needed. Other approaches can require significant rework.

4.5 Anatomy of activity

This section makes some general points in addition to those brought out in the example. Firstly, the general pattern of analysing activity is powerful. It is illustrated in Figure 18 and it shows that, at least from a modelling perspective, the activity itself is simply composed of its identified participants. This highlights that the results of the analysis are only as good as the analysis (a motive for conducting good analysis) but there is always more going on than is economical to analyse and model. Judgment here comes with experience.

From the earlier diagrams it can be seen that (the...) some? participants can also participate in more than one activity simultaneously, although care should be applied to analysis of this as it is unlikely that it is exactly the same state of that participant that is compared. (It may be a different overlapping state or, after further analysis, different parts of the same participant). In addition, a good test of the analysis can be to test whether it is possible to go to more detail. Drawing on the brickwork example we can extend the analysis of the bricklaying activity and identify what happens to individual bricks, batches of mortar, timings, etc.[16]. While for bricks there may not be a requirement to record the provenance of their sourcing, there may be strict requirements for other activities that place onerous information requirements on the traceability of materials and what has happened to them prior to (and during) particular activities.

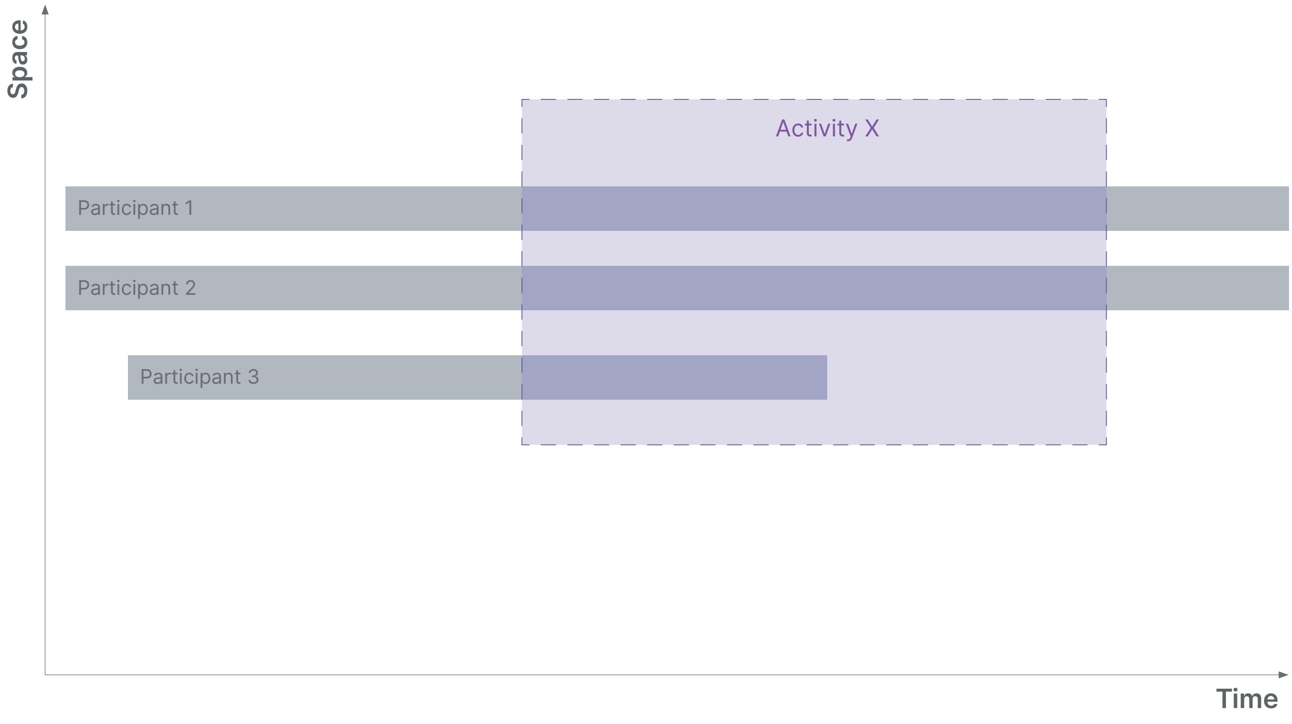

Figure 19: Addition of identified activity

A basic pattern for any activity

This apparently simple pattern for analysing activity, by identifying the participants that are involved and extending the analysis of their lifecycles (and their composition), is a powerful technique. It is an essential pattern that enables the subsequent capture of information requirements and mapping to the IMF.

An interesting part of the brickwork implementation activity is the time that the mortar takes to set. The wall with the wet mortar is not the only participant in the activity of its setting (this activity is not marked on the diagrams but it nonetheless happens). The environment that interfaces with the wall is also a participant as it will supply material (e.g. carbon dioxide), thermal energy and result in drying at exposed surfaces. While this may not be modelled, it is easy to identify that activity involving these and other environmental participants can be critically important.

This analysis can therefore also support process improvement and greatly improve the ability to develop plans and monitor progress against them, enabled by the input of information created as work is conducted.

This approach is compatible with starting from the top level down and from integrating detailed analysis of parts of the system activity. It can also benefit from using known activity patterns for particular activities (the brick wall example, when taken to a conclusion, may be a seed for analysis of other, similar brick wall lifecycle activities). The goal is to model all activity to an appropriate level of detail to enable it to be planned for and managed well, with the desired results. Initially this can seem an overwhelming task, but a structured approach as outlined in this study can make it straightforward and compatible with professional, established approaches to engineering and operation of Built Asset Systems. Performing this thoroughly on a large system is a complex undertaking and can benefit from the Systems Engineering skills and processes mentioned in 2.3. However, there is value in undertaking this analysis on component parts of the system or for areas of activity for which there is an opportunity and enthusiasm to conduct a more local analysis to gain familiarity with it prior to conducting it in a bigger way.

Figure 19 provides an outline of the method described in this document.

The activity of capturing the information requirements, mapping to the IMF Reference Data Library and integration in a suitable information architecture can take place using the results of this analysis. Documents on how to address them will be released as the IMF is developed.

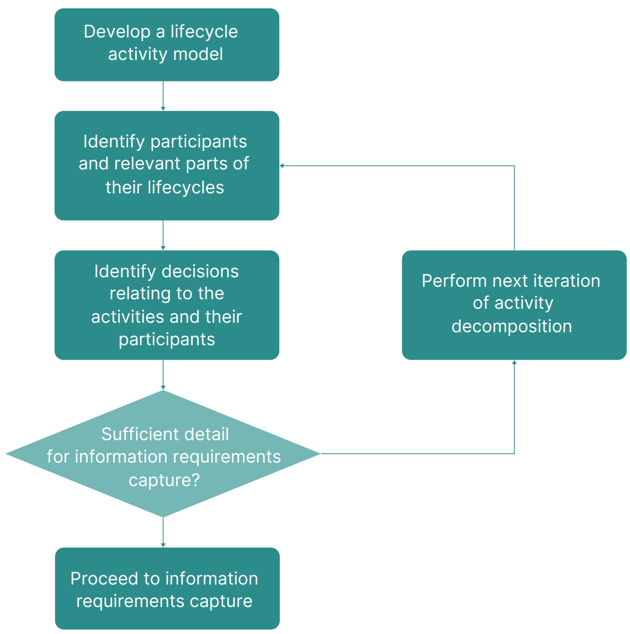

Figure 20: Outline process for identifying decisions that require information

5. Dealing with existing & legacy systems

It is all very well looking at the lifecycle of systems that do not yet exist but most Built Asset Systems that will be in existence in 20-50 years are already in operation today. Many will need to be upgraded at some point; to improve their performance, increase capacity or rerole the system entirely. Examples of these upgrades might include energy improvement initiatives, adding platforms or electrifying the lines at a rail station or converting an office block to accommodation apartments. Some existing systems will be decommissioned and disposed of. These activities concerning existing systems will require decisions and, where possible, can be conducted more efficiently if data are available to support them.

Although often cited as a barrier to the adoption of integrated information management in Built Asset System management, there is considerable benefit to be derived from the analysis of what is already in these physical systems and what information about them is required to support lifecycle processes. This can be seen as a bootstrapping activity for the increased use of information in the management of these systems[17]. Conducting this analysis can be seen as an unplanned cost but, if conducted well, a considerable benefit should result, ensuring that lifecycle costs are lowered. One of the major benefits of analysing legacy Built Asset Systems is that much of it, and activity relating to it, is in existence already so is arguably easier to assess.

One of the challenges of legacy Built Asset Systems is the portfolio of data that already exists to support them. It is common for this data to be piecemeal, maintained for only short periods of the asset's lifecycle, inconsistent and held in disparate files/systems. Even when stored in a common data environment or in an asset management system the challenge of keeping the "As built" or "current status" of the system is not much alleviated. Unless the specific information that is required can be accessed, updated (e.g. by the addition of new data records and not by the deletion of 'current') and created (when nothing previously existed) the task of doing this in aggregated datasets such as drawing or application-specific files is onerous. It can be better to create a new baseline of data rather than trying to maintain files that were not intended to support the information management lifecycle.

6. Conclusion

This study has introduced the need for a lifecycle view of activities involved in any part of a Built Asset System's existence, even many years prior to its being constructed. The analytic approach quickly reveals that everything involved as participants in these activities also has a lifecycle that may need the analysis method applied to it too. If performed with sufficient rigour, the analysis will identify the decisions made at all the points at which information is required (even if some of these are dependent on events, such as those that have associated risk).

The context of this activity analysis has been presented in the lifecycle of any Built Asset System and an indicative range of activity associated with each lifecycle stage has been illustrated. While it may appear to be a large number of activities, this is the reality of large systems engineering activities today. The only way to avoid waste in such undertakings is to rely on information that is fit for the purpose of engineering and operating systems at this scale. The need to do this is recognised by the Systems Engineering community. There is no escape for information management activity as it too is a key element of an integrated approach to lifecycle activity.

An initially simple activity analysis example quickly reveals the easily overlooked decisions that will require information in some form, often dependent on activity that occurred a long time prior to the decisions and perhaps in an entirely different organisation and location. If this information is to be available when needed as data, then it is critical that this is identified through analysis and the quality of that information recorded for the relevant activities to use (including all relevant activities in the BAS lifecycle, such as procurement, information management and supervisory activity).

An additional benefit of this integrated lifecycle analysis approach is that the information-requirements capture and the creation of the information itself, based on the requirements, only needs to take place once. This presents the opportunity for significant lifecycle savings in addition to the reduction of waste occasioned by not having the required information available when required (as is typically the case today).

Finally, with suitable analysis all the identified activity can be modelled using a suitable data model and ensure it is kept at the required quality by suitable information management. This is an example of what the IMF is implemented for, with the FDM at its heart to ensure a consistent and rigorous data-modelling foundation.

Footnotes

1 For example: https://dictionary.cambridge.org/dictionary/english/activity

2 https://dictionary.cambridge.org/dictionary/english/system

3 An egregious example of what can go wrong the Berlin Brandenburg Airport stands out. The UK also has examples of infrastructure projects that have gone significantly over time and budget.

4 As introduced earlier, they are all spatio-temporal objects.

5 It is unlikely that the 'real' world is at fault: it is more likely that the data are deficient! Do not forget that the data arejust a model-based representation of the real material object. The quality of these data should only be as good as it is required to be; no more… and certainly not less.

6 This does not mean that there is no need to understand the ontological* commitments in the FDM. However, it does mean that by making careful choices for the IMF there is a ready route to enable consistent data as a "foundation of Systems Engineering".

7 https://en.oxforddictionaries.com/definition/implementation

8 A lot of activity may influence the Preimplementation work but judgement should be applied to ensure that it is directly related to the intended Built Asset System itself. A simple test is that it should cover all activity that directly affects decisions at this lifecycle stage and that, ideally, for which there is direct governance/funding.

9 Mechanical, Electrical and Plumbing

10 https://www.incose.org/about-systems-engineering/se-vision-2025

11 General Certificate of Education

12 It is not always a good idea to start with these but generally they provide a sensible starting point and can be appropriate to the task under analysis. Trust in these processes can be improved by this type of analysis.

13 While it may be said that those familiar with building brick walls will 'know' what is involved, the point of the use of computers and information is to capture what is necessary to enable such activity. Computers do not have the benefit of this knowledge and humans involved typically will not know what is needed concerning the lifecycle of all the parts that are used in the task (and output from it). This is why information management of the right quality is a foundation to accomplishing this activity happen as required.

14 The equivalent in England would be Building Regulations Approval.

15 An example can be found here: https://www.aberdeenshire.gov.uk/planning/building-standards/apply-for-a-building-warrant

16 This may be required to be performed in considerable detail for some specialist applications such as using individually specified bricks or pre-cast blocks in radiation shielding for healthcare applications like proton beam therapy.

17 Even if there is an information deficit resulting in partial population of data models relating to these existing systems, there is considerable value in generating structured information records of such systems.

7. Appendix

Mapping Industry Process Models to the BAS Lifecycle Process Model

The table below provides a summary mapping of published industry and sector process models relating to large infrastructure systems, built assets or investments relating to them. There are two messages to take from this mapping:

1. Not many of the industry and sector process models cover a full lifecycle.
2. They map in a straightforward way to the BAS Lifecycle Process Model and can provide a useful (and in some cases mandatory) structure for activity analysis in the industrial sectors that they are aimed at.

		Pre-implementation	Implementation	Operation	Disposal
i	RIBA PoW 2008	A, B, C, D, E, F, G, H	J, K, L	L	
ii	RIBA PoW 2013 & 2020 Stages	0 – Strategic Definition 1 – Preparation and Briefing 2 – Concept Design 3 – Spatial Coordination 4 – Technical Design	5 – Manufacturing and Construction 6 - Handover	7 - Use	
iii	OGC Gateways & Infrastructure and Projects Authority: assurance review toolkit	0, 1, 2, 3, Dp1, Dp2	4	5	
iv	Network Rail GRIP Process	1, 2, 3, 4, 5	6, 7	8	
v	Designing Buildings Wiki	1, 2, 3, 4, 5, 6, 7	8, 9	10, 11	

		Pre-implementation	Implementation	Operation	Disposal
vi	Scottish Construction Procurement Journey	Outcomes & Business Case Justification, Procurement Strategy, Consultant/Contract Selection	Construction and Consultant Contracts	Asset Use	
vii	Soft Landings BSIRA	1, 2	2, 3	4	
viii	CIC Scope of Services	1, 2, 3, 4	5, 6		
ix	Office for Nuclear Regulation Decommissioning Process			One	Two, Three
x	Process Industries Model Process Plant Engineering Activity Model (13)	Conceptual & Detailed Engineering Design	Construct & Commission	Operate & Maintain	Decommission
xi	IAEA Safe and Effective Nuclear Power Plant Life Cycle Management towards decommissioning	Design	Construction & Commissioning	Start Operation, Design Life, Life Extension, Cease Operation, Cold Operation	Decommissioning, Entombment, Safe Enclosure, Dismantling
xii	Intelligent Transportation System Vee Lifecycle Model, U.S. Department of Transportation, Federal Highway Administration, California Division, (8)	Regional Architecture Concept Exploration Planning and SEMP Concept of Operations System Level Requirements Subsystem Requirements Detailed Design	Development & Implementation Integration, Test and Verification	Operations and Maintenance & Validation Changes and Upgrades	System Retirement Replacement

		Pre-implementation	Implementation	Operation	Disposal
xiii	UK BIM Framework, Government Soft Landings guidance 2019 Outline Stages only (see BS 8536 below)	Strategic Assessment / Outline Business Case Stage Final Business Case / Briefing Stage Design and Construct Stage (Design part only)	Design and Construct Stage (Construct part mostly) Pre-handover Stage	In-Use / Operational Stage	
xiv	NHS Scotland BIM Asset Lifecycle Process Map Based on Scottish Capital Investment Manual Framework Process	Stage 0 Strategic Information Stage 1 Initial Agreement Stage 2 Outline Business Case Stage 3 Full Business Case	Stage 4 Implementation	Stage 5 Evaluation	
xv	UK Government Soft Landings Revised guidance for the public sector on applying BS8536 parts 1 & 2 (see BS8536 in Standards Table below)	0 – Strategy 1 – Brief 2 – Concept 3 – Definition 4 – Design	5 – Build and Commission 6 – Handover and Close-out	7 – Operation [and End of Life]	7 – [Operation and] End of Life
Xvi	UK Treasury Green Book	Business Case Options Development, Shortlist Appraisal, Cost Benefit Analysis and Presentation. Monitoring and Process Evaluation.	Monitoring and Process Evaluation	Impact Evaluation	

Table 3: Survey mappings of available industry process/activity lifecycle models to the BAS Lifecycle Process Model

The next table maps some Standards that make use of a lifecycle approach to their areas of application. In the case of BS EN ISO 19650 Parts 2 & 3 have a project focus but each part is dedicated to different stages of the LPM.

		Pre-implementation	Implementation	Operation	Disposal
a	BS 8536-1:2015, Briefing for design and construction – Part 1: Code of practice for facilities management (Buildings infrastructure)	BS 8536-1 stages: 0 Strategy, 1 Brief, 2 Concept, 3 Definition, 4 Design	BS 8536-1 stages: 5 Build and Commission 6 Handover and Close-out	BS 8536-1 stage: 7 Operation [and End of life]	BS 8536-1 stage: 7 [Operation and] End of life
b	BS ISO 55002:2018, Asset Life Cycle and Strategic Asset Management Plan	Conception to Acquisition		Operation	Disposal (including post disposal liabilities)
c	ISO/IEC/IEEE15288:2015, System Life Cycle Stages	CONCEPT DEVELOPMENT	PRODUCTION	UTILIZATION SUPPORT	RETIREMENT
d	BS EN ISO 19650-2:2018, Organisation and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – Information management using building information modelling. Part 2: Delivery phase of the assets		1 – Assessment and need 2 – Invitation to tender 3 – Tender response 4 – Appointment 5 – Mobilization 6 – Collaborative production of information 7 - Information model delivery 8 - Project close-out (end of delivery phase)		

		Pre-implementation	Implementation	Operation	Disposal
e	BS EN ISO 19650-3:2018, Organisation and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – Information management using building information modelling. Part 3: Operational phase of the assets			1 – Assessment and need 2 – Invitation to tender / request to provide service 3 – Response to invitation to tender / request to provide service 4 – Appointment 5 – Mobilization 6 – Production of information 7 - Information model acceptance by appointing party 8 – AIM aggregation	

Table 4: Asset Lifecycle Stages Referenced in Selected Standards mapped to the Built Asset Lifecycle Process Model

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