Systems engineering and the project delivery process in the design and construction of built infrastructure

Jennifer Whyte
Imperial College London, Department of Civil and Environmental Engineering, j.whyte@imperial.ac.uk

Author draft – please contact author for published version, when available.

Abstract

How can a systems engineering approach be applied to the project delivery process in the design and construction of built infrastructure? First, this paper articulates how infrastructure can be seen as *a system of interest*, a complex product system that is operated and delivered through enabling production and work systems. Second, it considers *systems operation*, where research in the systems engineering discipline shifts attention from 'operator error' (and root causes) to the systemic accident factors. Third, it considers *systems development* and how a formal model of the development process, the classic V diagram, differs from the standard representations of production used in the design and construction of built infrastructure emphasizing systems architecture and systems integration. Fourth, it considers *production systems* in terms of the locus, organization and activities involved in fabrication and assembly. Fifth, it considers *infrastructure systems* from the broader perspectives of long term ownership and operation of assets, critical infrastructure, and a shift from a linear to circular economy. The paper concludes by discussing where further research is needed. This is both in relation to the emergent properties, flows of physical material, information and costs associated with infrastructure as a complex product system and in relation to the enabling work systems for production (design and construction) and for operation, maintenance and disassembly.

Keywords: *Systems Engineering; Production Systems; Infrastructure; Project Delivery*.

Introduction

There has been significant interest in the application of a systems engineering approach to the production of buildings and infrastructure [1-4], with USA Department of Energy directive [5]; Department of the Transport guidance [6]; and the Netherlands requiring the use of systems engineering in infrastructure projects [7]. The term 'systems engineering' has been used since the 1940s, and many associated techniques developed out of the need to deliver projects in the USA military and aerospace industries that were novel and complex in nature [8, 9]. This use of systems engineering draws attention to topics such as: requirements analysis, functional allocation, systems architecture, partitioning (or decomposition), interfaces, trade-off studies, baselines, configuration management, verification and validation, testing and systems integration. In 1954 Ramo-Wooldridge Corporation was employed as system integrator for the Atlas project that developed ballistic missiles [8-10], with responsibility to: *"coordinate the work of hundreds of contractors and development of thousands of sub-systems"* [11: p. 38]. Although there are complex supply chains associated with major infrastructure projects, the use of systems engineering approaches to partitioning and integrating the work in civil engineering is relatively immature: there remain questions about how to translate concepts from seminal 20th century projects, such as Atlas, to contemporary infrastructure [9].

A systems engineering approach to built infrastructure has significant potential [2, 4]. The lack of integration in infrastructure projects can lead to serious issues only being identified in the commissioning phase, as in the recent example of Berlin Brandenburg Airport. This airport couldn't open when planned in 2012, with officials noting 20,000 issues that needed to be addressed before opening (this later rose to 150,000 issues) [12]. It is now planned to open in 2018 or 2019. Such inadequate planning and inability to integrate systems is costly: maintenance on this already built, but not yet operational airport is €16 million per month maintenance [13]. Fire safety issues were a reason to delay opening, with a concern that the ventilation system, which was designed using tunnels rather than the more conventional chimneys, would not be able to meet the legal requirement of removing smoke from the passenger terminal within 15 minutes [12]. When open (if it does open), the design of the passenger and baggage check-in, which is hard to change, will limit the number of passengers [12].

One reason it is timely to reconsider systems engineering approaches in the design and construction of built infrastructure is because advanced manufacturing techniques (such as robotics; Building Information Modeling (BIM); embedded sensors; off-site and near-site manufacturing) are becoming more widely used. When infrastructure as the system of interest is delivered through advanced manufacturing techniques, it requires upfront decisions and commitments on systems architecture and integration in the early stages of the project, with standardization of components and interfaces. Infrastructure is a complex product system and is increasingly cyber-physical in nature: this has consequences for the enabling production systems and associated work systems. Systems engineering provides an approach to understanding the extent of changes involved, for example, in a change of locus of assembly from the site to off-site factory; the change of design authority within the supply-chain and in the move to more extensive use of digital information for monitoring and adaptation in production, as well as in operation.

A second reason it is useful to think of the system is to reconsider system boundaries. The conceptualization of infrastructure as a complex product system with enabling work systems for design and construction is broadened by a focus on critical infrastructure, long term ownership and operation of infrastructure assets and on their life-cycle. Moving from a linear to a circular economy brings into view new issues and opportunities, such as that of 'urban mining' [14] and the reuse of existing materials as well as use of raw materials in the production process. This is important because construction accounts for 36% of raw materials consumption in Organization for Economic Collaboration and Development countries [15]; and because debates about critical infrastructure draw attention to the wider context in which infrastructure is created for society and its range of intended and unintended uses. It is not fully captured in the input, output models and representations that are often used for communication in systems engineering. A classic approach in systems engineering is to focus on the key characteristics of the system, as a means to reduce complexity: *"by taking a 'systems view' of the whole project and breaking it down into smaller, simpler, interacting parts which can be organized and managed more easily."* [2: p.10]. New questions arise about how best to model systems.

This paper addresses the research question: *How can a systems engineering approach be applied to the project delivery process in the design and construction of infrastructure?* It does so through a critical review of how systems engineering is explained and discussed in the extant standards, guidance and research literature and consideration of their applicability to, and the broader questions they raises for, researchers and practitioners interested in the design and construction of built infrastructure. First, the paper articulates how infrastructure can be seen as a *system of interest*: a complex product system that is operated and delivered through enabling work systems. Second, the paper considers *systems operation*, where there is substantial work in the systems engineering discipline on the safe operation of complex sociotechnical systems. Third, it considers *systems development*, and how a formal model of the development process for complex systems, the classic V diagram, differs from the standard representations of production used in the design and construction of built infrastructures. Fourth, it considers *production systems*. The literature on systems engineering sees the production system as an enabling system and focuses more on the development and operation of complex product systems than on their fabrication and assembly. Hence this section draws where appropriate on a broader range of related literatures. Fifth, it considers *built infrastructure systems* from the perspective of the long term ownership and operation of assets and a shift from a linear to circular economy. Finally the paper draws out practical implications of the current state-of-the-art knowledge and relates systems engineering approaches to aspects of project delivery such as lean construction, Integrated Project Delivery (IPD), Building Information Modelling (BIM) and off-site manufacturing. The paper concludes by discussing where further research is needed. This both in relation to the emergent properties, flows of physical material, information and costs associated with infrastructure as a complex product system and in relation to the enabling work systems for production (design and construction) and for operation, maintenance and disassembly.

The system of interest and its stakeholders

Systems engineering guidance is represented in the International Council on Systems Engineering (INCOSE) handbook and in standards such as ISO/IEEE 15288, which describes a systems of interest, where: *"the perception and definition of a particular system, its architecture and its system elements depend on a stakeholder's interests and responsibilities"* [16: p.11]. This articulates system characteristics as an integrated defined set of elements with relationships between elements and defined boundaries (in relation to needs and solutions) and as product or service [16: p.11]. Within such a system of interest, sub-systems can themselves be seen as systems, with humans seen as either external to or elements within these systems. Both the standard and the handbook describe a complex product system, such as infrastructure, supported by enabling systems such as the production system and associated work systems.

As shown in Figure 1, the classic approaches to modelling processes in systems engineering start from input-output models, which show a process, constrained by controls and supported by enablers, widely used in the INCOSE literature [e.g. 2: p. 17]; or from the classic control loops that start to represent how information on a process is measured and controlled indirectly (through sensors and actuators) and understood in relation to reference data and models in closed and open systems.

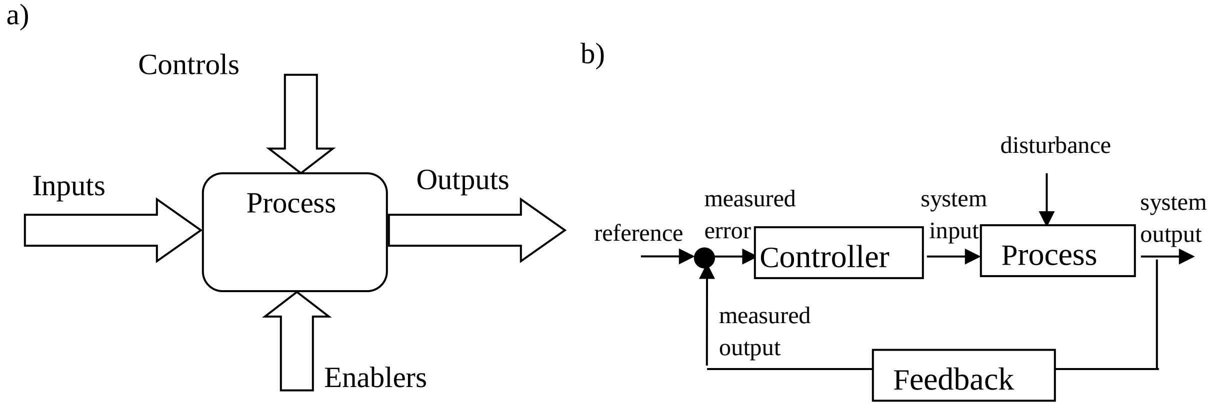

Figure 1: Simple systems models: a) input-output models, source: [2: p. 17]; and b) drawing on control theory, an example of a simple model of a closed control loop associated with system operation

Examples of systems engineering in infrastructure are used in the INCOSE handbook (version 4), including the Øresund Bridge, which links Copenhagen and Malmö [17]. The handbook argues that on infrastructure projects: *"The greatest benefits of applying SE principles is gained in the systems integration and construction stage"* [17: p.168]. Yet much current advice from systems engineering to built infrastructure lacks specificity. For example, Emes, Smith et al. [18] provide 5 generic principles with the aim of anticipating and responding to *"a changing environment with a focus on achieving long-term value for the enterprise."* These are: 'principles govern processes', 'seek alternative systems perspectives', 'understand the enterprise context', 'integrate systems engineering and project management' and 'invest in the early stages of projects'. The INCOSE Infrastructure Group has moved forward understanding of the application of systems engineering to infrastructure through its guide, noting differences with high technology and mass production sectors, where: *"The design process for LIPS [large infrastructure projects] tend to be relatively well established and reasonably optimised and any complexity to be addressed lies more in issues of interfaces, procurement and constructability, given the specific political, commercial and local conditions, than in the design of a certain type of bridge, the particular alignment of a railway or highway or the type of power generation plant."* [2: p. 10]

Yet the application of systems engineering in project delivery does not guarantee success, especially as this is a different context for the application of systems engineering than the defence projects on which it was developed. The example used by Hughes [9] of systems engineering's application in this sector is the Central Artery/Tunnel Project, known as the 'Big Dig', in Boston. He contrasts the 'open postmodern style of coping with complexity' on this project [9: 254] with that of the earlier defence projects, which can be seen as more 'closed systems'. The dividing of a system into subsystems is the same as on earlier projects such as ATLAS [9: 240], and hence the project faced the same issues of coordination of the design and development of subsystems or packages, e.g. across the 132 construction packages. Greiman

[19], who worked on the project, describes the importance of a project scope control program, with a project controls plan, technical scope statement, work breakdown structure, contract services, change control program, early identification and trend programs and quarterly assessment. Hughes, however, notes how such infrastructure projects are 'congealed politics': open systems with many external factors that affect their success [9: 197]. He thus writes about the 'open, participatory, multidisciplinary' techniques that are mobilised in this context [9: 230]. Less optimistically, Flyvbjerg [20, 21], has highlighted how, on infrastructure megaprojects, politicians and engineers overestimate benefits and delivery capability and strategically misrepresent costs. Lundrigan et al. [22] argue that megaprojects consist of two structures: a "core" that engages with stakeholders and shares control over goals and high-level design choices and a "periphery" that is the supply-chain that delivers but lacks authority to change high-level goals and design choices. There are questions about the applicability and reach of systems engineering approaches across this organizational landscape.

Systems operation

Within the systems engineering discipline, there has been significant research on systems operations, particularly with a focus on system safety and analysis of accidents in relation to system control. This work has drawn attention to the work systems associated with operations and the systemic nature of accidents and errors. It shifts attention away from a focus on 'operator error' and even the broader analysis of 'root causes' to consider the chain of events that leads to safe or unsafe system operation, and how a whole system operates together (systemic accident factors). Much research on socio-technical systems and human systems integration has taken place in this context. At the heart of such analyses is the 'control loop' in which Leveson [23] inserts the computer to see the human controllers interact with physical processes through the automated controllers, actuators and sensors.

Early work recognized that the complexity and interdependence of the organizations that operate complex technological systems may lead to systems accidents [24] due to one failure cascading through the system. Leveson [25] clarifies how safety and reliability are different properties of systems, where a system with unreliable components may be safe; while through a 'component interaction accident' one with reliable components may be unsafe. In Leveson [23] she highlights how computers mediate operators knowledge of the system, thus in major system accidents, such as Chernobyl and Three Mile Island ambiguous readings and faulty indicators play a role in leading to unsafe operations. This literature has significant insights about work systems that are useful in infrastructure, and has also led to tools, such as "Safetyhat" a software tool for safety hazard analysis, that has been developed for use in transportation systems[1]. Yet, for the professionals involved in the design and construction of infrastructure, the system is not stable but is in development and this adds to the complexity.

[1] https://www.volpe.dot.gov/infrastructure-systems-and-technology/advanced-vehicle-technology/safetyhat-transportation-system [accessed 30/10/2017]

Systems Development

The development of systems engineering was motived by the drive to improve acquisition and performance as complex systems are delivered through distributed supply-chains. The INCOSE website articulates this interest in the development of complex systems: *"Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs."*[2] In research on infrastructure, Hoeber, Alsem et al. [26] likewise characterize systems engineering as an interdisciplinary life-cycle approach with a system breakdown structure providing for the characterization of sub-systems.

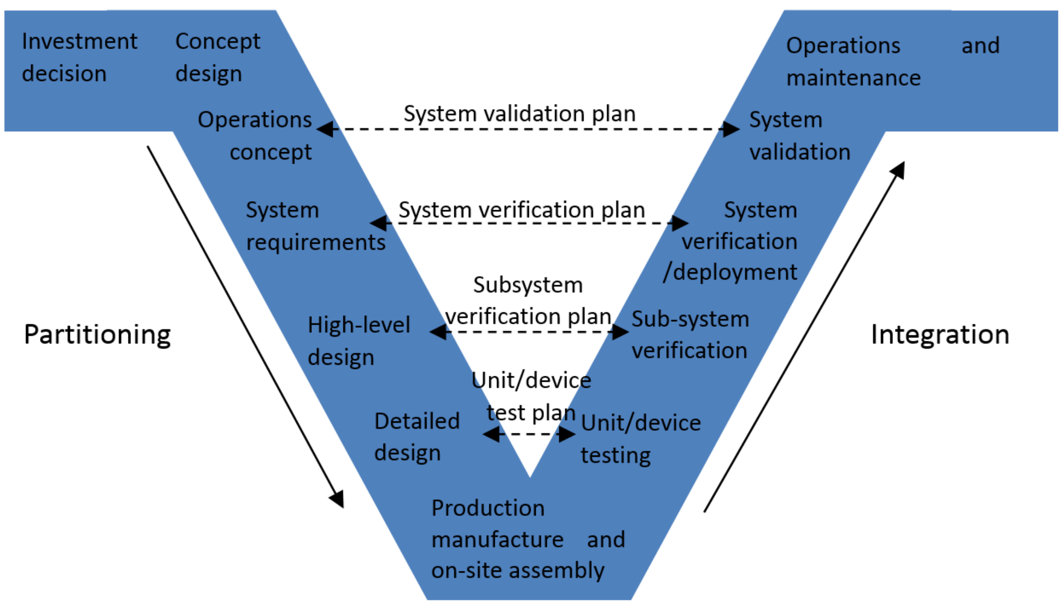

Figure 2: The delivery processes represented in the systems engineering 'V' diagram [adapted from source:6]

This systems engineering approach is often summarized in formal models, including the many variants of the 'V' diagram, shown in Figure 2. This differs from the earlier models used in systems engineering, such as the waterfall model, which showed sequential stages with feedback loops. The standard process models used in the construction sector, typically show sequential stages with feedback loops. An important aspect of the V diagram is the recursive partitioning of the systems architecture so that scopes and interfaces can be defined contractually and outsourced to be delivered separately across a complex supply chain. Systems architecture and partitioning of the system enables individual parts, components, units, subassemblies and sub-systems involved in built infrastructure to be fabricated and assembled separately by different firms. The systems engineering guidance on infrastructure clarifies how: *"The design solution is represented by the System Build Configuration (SBC) as decomposed into the System*

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[2] http://www.incose.org/AboutSE/WhatIsSE [accessed 30/10/2017]

Breakdown Structure (SBS) and allocated according to the Work Breakdown Structure (WBS) to each contracted party as defined in the Organizational Breakdown Structure (OBS)" [2: p. 18]. Research on integrated building design by Baudains et al. [27] has taken the systems paradigm to articulate constrains, functional relationships and physical relationships in order to understand the performance of a building in relation to different aspects, such as space, structure, organization and operation.

Systems integration enables these parts, components, units, subassemblies, subsystems and systems to work together as a whole. Where integration is a driver for systems architecture, the ability to consistently fabricate and test different sub-sets of the system may affect the partitioning of the system through the product-breakdown structure. There are different strategies for integration: aggregation; global integration; integration within stream; incremental integration; sub-set integration; top-down integration; bottom-up integration; criterion driven integration; and reorganization of coupling matrices [17].

On large infrastructure projects: *"a proof of concept is not normally developed, therefore it is more difficult to identify missed requirements and design issues"* [2: p. 21]. Within research on systems engineering, many tools and methods have been developed to facilitate the processes of systems partitioning and systems integration. An example of a method is model-based systems engineering (MBSE), which focuses on exchanging information between engineers through domain models rather than documents. One approach to developing suitable models is to use a universal modelling language (UML) based language, the Systems Modelling Language (SySML). Thus, for example, Geyer [28] conceptualizes (but does not implement) a parametric systems modelling approach for sustainable building design using SySML to complement IFC and gbXML standards, as a way to explore possible variations, physical–technical interdependencies, evaluation information, flows and behaviors by representing multidisciplinary dependencies for performance-oriented planning.

Projects quickly become complex. A project of only fifteen aspects, eight of which are uncertain and can be resolved in one of four possible ways, has 65,536 possible states [29]. One example of a tool designed to manage the complexity is the Design Structure Matrix (DSM), which makes visible the interdependencies between different components or tasks [30-32]. Recent work has begun to look at how the same process database might drive the different visualizations (matrices, charts etc.) that are helpful in decision-making on complex projects [33]. Researchers have also examined firm capabilities and strategies for systems integration, including modular systems architectures [34-36].

Production Systems

Body A production systems is seen as an example of an enabling system in the INCOSE handbook [17]. In the discussion of systems operation and systems development in the extant literature there is a strong focus on systems architecture and its consequences for systems integration and safe operation. There is relatively little attention to the production process, and the operators involved in fabrication and assembly (as opposed to ongoing operations and maintenance) of complex systems. This section considers related streams of research on production systems, manufacturing (or production) systems engineering and innovation in complex product systems before the next section turns attention to construction work, and the systems associated with the design and construction of infrastructure.

New understanding of production systems was developed in the mid-to-late 20th century. Starting from empirical research on both the organization and the technologies of production, this moved away from the Marxist critiques of the capitalist mode of production, on the one hand, or Adam Smith's economics of the division of labor on the other.

Early research articulated relationships between firm performance, technologies of production and work systems. Woodward's [37] key insight from a statistical analyses of firm performance was that the best performing firms had organizational approaches that suited their technologies of production (unity production, mass production, continuous process). She found, for example, that higher technological complexity was associated with a shorter span of control and hence more levels of authority and managerial personnel than mass production systems. The relationship between the social and technological in the associated work systems was explored by the Tavistock institute. In the context of high absenteeism and poor workforce relationships in the British coal industry, their research examined a mine in which improved roof control had enabled 'shortwall' mining [38]. Here, they encountered unexpected cooperation between task groups, personal commitment, low absenteeism, low accident rates and high productivity. Their focus became understanding the whole sociotechnical system within which work is accomplished, with the work system understood as set of activities that made up a functional whole rather than single jobs [38].

Distinct disciplines of operation research and systems engineering were developed in the 20th century[8], where operations research addressed how to deploy existing resources, through mathematical analyses and data collection across projects, and systems engineering had a stronger focus on the planning for use of new resources within a project. Production is a highly interdisciplinary field and these disciplines are interconnected and have become a source for each other in the development of new understanding of production systems. Highly influential work on the Toyota Production System and lean manufacturing [39], developments in the mathematics of queuing theory [40] have informed new developments, such as for example the development of Agile System Engineering [e.g. 41].

Researchers take the 'production systems' as a system of interest across a number of related disciplines, but conceptualize this system differently. A useful idea within the research on manufacturing systems engineering is to follow the flows of material resources, information, and costs through the system in order to understand it [42: p.6]. While some work is narrowly focused on the factory, other work maps out the broader context of and logistics involved in material supply, manufacturing, assembly, sales, services and use. As an example of the former approach, with a focus on the factory, recent work on production systems engineering has produced a mathematical model of a production system according to five components: type of production system (how machines and material handling systems are connected); models of machines; models of material handling devices, rules of interactions between machines and material handling devices, and performance measures [43]. As an example of the latter approach, recent research on distributed approaches to manufacturing is starting to map out the broader network of activities associated with production as a system of interest [44].

Research on innovation takes a broad systems perspective to production, contrasting how technological innovation occurs in the complex product systems that are delivered through projects involving a distributed supply chain with mass production contexts [45]. In the delivery of complex product systems, particular firms are seen to take a 'system integrator' role, with recent research drawing attention to modularity, and to the system integration challenges within both the firms [34, 35, 46] and complex projects [47-49]. Winch [50] highlights how it is difficult to identify one firm as 'systems integrator' in construction where owners and operators may not be identified and the delivery client for the project is relatively powerful in relation to the ecology of firms involved in its delivery. Researchers map out a range of inter-organizational structures involved in different kinds of procurement and delivery approaches such as design build; design-bid-build; inter-organizational structures [51]. Miller [52] described how the engineering systems integrator for infrastructure is concerned with optimizing the project delivery and finance configuration with different approaches leading to different innovations and integration approaches.

Built Infrastructure Systems

In the preceding sections we have examined how systems engineering approaches systems use; systems development and production systems. In this section we turn attention to other specific characteristics of built infrastructure as a system of interest (and as a system of systems). At a broad level, Matar et al. [53] provide an approach to SySML modelling for sustainability in infrastructure involving 1) natural systems that make up an environment system of systems (SoS), the atmosphere, lithospheric system (material resources); hydrosphere; biosphere and energy; 2) construction product SoS, architectural, structural, mechanical, electrical; 3) business management, design management, project planning and management, construction and facilities management. The focus in this section will be on the longevity of infrastructure; the interconnections between systems; the critical nature of some infrastructure; the roles and perspectives of infrastructure owners; the cyber-physical nature of infrastructure and the flows of materials and information through the work-systems and production systems associated with infrastructure.

The longevity of infrastructure systems bring particular challenges. These are recognized in INCOSE guidance, which notes that: *"Long life systems will have functional upgrades and system element replacements throughout their life"* [17: p. 236]. Here it is useful to distinguish and focus on different systems of interest within infrastructure, as: *"Infrastructures like tunnels, water barriers etc., are designed and built for a long asset life (mostly 80-100 years) whereas modern technology used within these infrastructures (e.g. tunnel ventilation systems) have a shorter lifespan and are often affected by changes to safety legislation and environmental compliance."* [2: p. 23].

The broader interactions between infrastructure systems are beginning to get attention, with the INCOSE handbook noting the *"interconnected system of infrastructure systems"* [17] and researchers identifying the interdependencies between infrastructures and systems of systems [54]. Physical interdependencies, and potential for clashes and conflicts across systems, are a particular issue in dense urban areas with significant existing infrastructure; but there are also interdependencies associated with the flows of material resources, information and costs. For example, new transport systems may have a significant energy consumption that requires policy making and technical solutions across traditional boundaries. The role of a broader set of stakeholders is recognized in recent work to develop new infrastructure business models through the formal modelling of user-infrastructure interdependencies using SysML [55]; and through the development of an interaction model to understand emergent dynamics and risks in institutionally complex projects (understood as systems-of-systems) that involve international organizations, public and community groups [56, 57].

Research on critical infrastructure takes a systems approach to considering vulnerability in terms of susceptibility and resilience [58]. This has developed new approaches to analyzing the interdependencies across different kinds of infrastructure [59] within nations and states. For example it has examined the appropriate design of power and water networks [60] to ensure continuity of supply. The cyber-physical nature of modern infrastructure has drawn attention from this community of researchers [61].

Infrastructure owners are thinking strategically about their whole portfolio of infrastructure assets, and the interactions with customers, suppliers, stakeholders, assets [e.g.62]. This involves a move away from the linear modelling of production systems, shown in Figure 1, and also used by authors in the production and manufacturing systems engineering literature [e.g. 42: p. 7].

Following the flow of materials through the production system can lead to new insight into how to make construction resource efficient and increase recyclability of materials through 'urban mining' and other techniques. This is important because the construction industry accounts for 36% of raw materials consumption in Organization for Economic Collaboration and Development (OECD) countries, with nearly 72 billion tons of raw materials entering the world's economic system in 2010; and a projected rise to 100 billion tons of raw materials a year by 2030 (OECD, 2015)[3].

CONCLUSION

There are useful strands in the literature on systems engineering and production systems that are relevant to extending our understanding of the project delivery process in the design and construction of built infrastructure. In relation to infrastructure, Table 1 considers the different systems, stakeholders, enabling systems including work systems and flows of information, materials and costs involved in different stages. While new questions arise about how best to model built infrastructure, development is deliberately represented twice here to emphasize the need to start from a consideration of systems as circular rather than linear.

	Development	Use	Demolition	(Re-)Development

[3] This point is also made in 3. Whyte, J.: 'The future of systems integration within civil infrastructure: A review and directions for research'. Proc. International Symposium of the International Council on Systems Engineering (INCOSE) IS 2016, Edinburgh, 18-21 July 2016.

Infrastructure as a complex product system	Cyber-physical assets and digital asset information *in development*	Cyber-physical assets and digital asset information *in use*	Cyber-physical assets and digital asset information *in demolition*	Cyber-physical assets and digital asset information *in development*
Stakeholders	Politicians; society; owner; financiers; insurers; regulators; delivery client; design consultants; construction contractors; supply chain including temporary works and material suppliers	Politicians; society; owner; financiers; insurers; regulators; operators; maintainers; users	Politicians; society; owner; financiers; insurers; regulators; demolition specialists; recycling and material recovery specialists	Politicians; society; owner; financiers; insurers; regulators; delivery client; design consultants; construction contractors; supply chain including temporary works and material suppliers
Enabling production system	Design, manufacturing and assembly	Operation and maintenance	Demolition	Design, manufacturing and assembly
Associated work system	e.g. Assembly on site	e.g. Operation, maintenance, Caretaker and cleaners	e.g. Urban mining	e.g. Assembly on site
Key interdependencies	Natural environment; raw materials; other resources; waste; neighbours; future users; other infrastructure systems	Other infrastructure systems;	From waste to new resources;	Natural environment; raw materials; other resources; waste; neighbours; future users; other infrastructure systems
Material flows	Raw materials; other resources; people; vehicles; waste	Energy; people;	Retrieval of high-value metals and other materials	Raw materials; other resources; people; vehicles; waste

Information flows	Digital asset information	Sensor data; Upgrades to operating systems	Digital asset information	Digital asset information
Cost flows	Public and/or private funding; payment of supply-chain	Payment from users to owner or operator		Public and/or private funding; payment of supply-chain

Table 1: Aspects of infrastructure system in development, use, demolition and (re-) development as a starting point for thinking about how systems engineering approaches can be applied to the project delivery process in the design and construction of infrastructure.

Systems engineering is a discipline that involve formal languages, models and tools for working across engineering disciplines and organizations; and for considering interfaces and interactions between physical components. A systems engineering approach is concerned with a systemic understanding of the operation and development of complex systems. In the extant literature on development there is a strong focus on systems architecture and its consequences for systems integration, particularly where this involves an ecology of firms across a distributed supply chain, with relatively little attention to the associated processes of production (fabrication and assembly). While the verification, validation and testing processes associated with systems integration draw attention to some aspects of production, systems engineering research that considers human-systems interaction (or humans as part of a system) has focused on the systems operator.

Which systems of interest should we consider in relation to design and construction of infrastructure? The infrastructure may be thought of as a complex product system, delivered through a complex project, with particular attention to the cyber-physical assets and digital asset information. An alternative is to take as the system of interest the enabling production systems or the associated work system. The idea of a work system is well developed in the literature [38] yet most recent work has considered operations. In looking at systems of work, there is a need to contrast the characteristics of the production worker with that of the operator of a complex product system, to understand how to draw on this earlier research. There are particular characteristics of their work that are related to the incomplete nature of the complex product. There is some extant work that takes a systems perspective in considering construction safety [63] and in prospectively identify vulnerability to uncertainty through analysis of construction projects as networks [64]. There is the potential to further consider and compare the different work systems that are involved in the design and production of infrastructure (e.g. related to different forms of fabrication and assembly processes), and to consider issues such as construction delays in the context of wider systemic issues.

Further research is needed in two main areas. First, there is a need for research in relation to infrastructure as a complex product, and increasingly cyber-physical, system, with associated emergent properties, flows of physical material, information and costs. There is the potential to follow the material resources involved in design and construction of a complex product system, from raw materials to processing, manufacturing and assembly, and beyond that to later disassembly and reprocessing. There is also the potential to follow the flows of information and/or costs as a way to understand the system. The systems engineering literature discusses the need for ‘transition systems’ [2: p.20] as a way to bridge between stages such as production and use, and here work has begun to examine the challenges of information hand-over [65]. There is also substantial work needed on systems integration. This is an area of interest to commercial and policy organizations, such as FIATECH, and broader related literature on relevant topics such as modularity, parts and lean construction; construction IT, and there seems mileage in extending the comparisons between construction and manufacturing [18], and developing new tools and approaches.

Second there is a need for further research in relation to the enabling work systems for production (design and construction) and for operation, maintenance and disassembly. There is relatively little research taking the design and construction of built infrastructure as a system of interest. Yet there is a long tradition of research on work systems, and a contemporary literature on systems operators, on which this can draw. There is a need for research to examine the work involved in the operation, maintenance and disassembly of infrastructure, but there is also a need for new research that considers the operators involved in fabrication and assembly, where we expect that the work will be affected by the complex cyber-physical system that is in construction as opposed to stable as it would be in ongoing operations.

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