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The future of systems integration within civil infrastructure

A review and directions for research

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Laing O'Rourke / Royal Academy of Engineering Professor in Systems Integration

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Centre for Systems Engineering and Innovation in Infrastructure

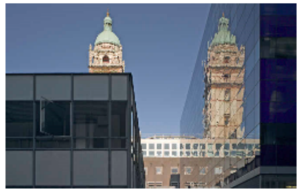
Our history - bringing systems engineering to the built environment

In order to enhance the capacity of the construction industry to respond to the environment and sustainability challenges Laing O'Rourke initially funded the creation of a Centre for Systems Engineering and Innovation at Imperial College London.

The Centre is in the Faculty of Engineering and is located in the Department of Civil and Environmental Engineering.

In the first five years, the Centre developed ways in which to bring world class process systems engineering and innovative science into building services technology and provided a focus for innovative teaching and research programmes.

This included a fully accredited part-time and full-time Masters Programme in Systems Engineering and Innovation that commenced in October 2011. Unfortunatley in September 2015, due to developments in industry, the Masters Programme has been suspended until further notice.



Annual distinguished lectures

2015 Annual distinguished lecture Professor David Oxenham

2014 Annual distinguished lecture Mr Mike StJohn-Green

2013 Annual distinguished lecture Professor Arnulf Grubler

Annual reports

2013/14 Annual Report

2010/13 Annual Report

MSc in Systems Engineering and Innovation

Systems approaches to reliability and resilience

Systems approaches in Engineering

Systems analysis of advanced ME issues

National energy systems and

Bringing Systems Engineering and Innovation to Civil Infrastructure

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A Faculty of Engineering initiative, hosted in Department of Civil and Environmental Engineering

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What is the future of systems integration within civil infrastructure?

INCOSE
INFRASTRUCTURE
WORKING GROUP

Applying Systems Engineering to Industrial & Infrastructure Projects

Systems Integration

What is Systems Integration?

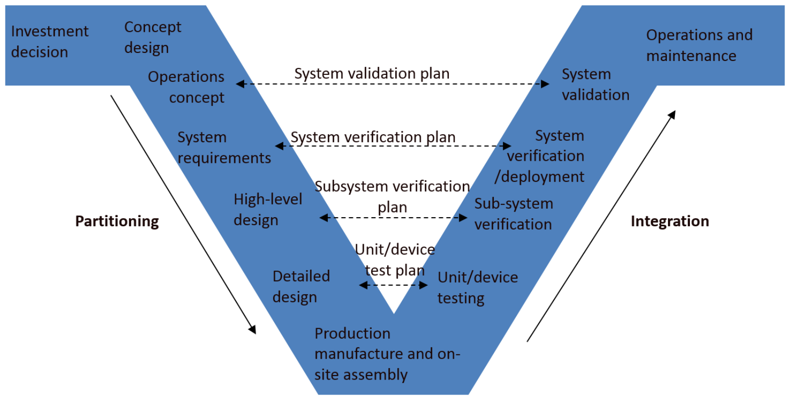
Systems Integration (SI) for the infrastructure industry is the integration of systems within a project, not just the electrical, mechanical, architectural and civil systems, but also all technical and human elements. SI emphasizes a holistic view, focusing on projects and the systems they are delivering as a whole. SI includes technical (functional, operational, logical, physical, geographical) interfaces as well as schedule-related and organizational interfaces. It is necessary to ensure an integrated solution from conception, through design, construction, testing and into service. It ensures changes during construction consider the impact on the designed solution and facilitates required modifications.

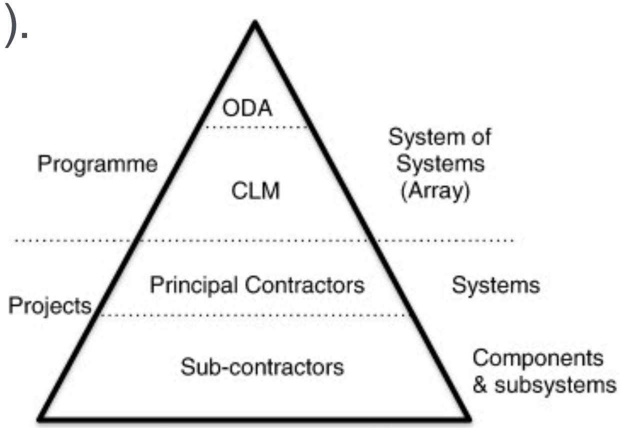
Large Infrastructure Projects (LIPs) benefit from consideration of SI aspects from the outset. Early contributions ensure the proposed solution and delivery strategy achieve the desired outcome by defining the target system configurations and resulting level of service at each implementation phase.

In Design-Build projects, some interfaces are not always identified or specified until late in the projects, creating

On infrastructure projects: *"The greatest benefits of applying SE principles is gained in the systems integration and construction stage"* (INCOSE, 2015: p.168).

Systems integration: *"Iteratively combines implemented system elements to form complete or partial system configurations in order to build a product or service. It is used recursively for successive levels of the system hierarchy."* (ISO/IEC/IEEE, 2015: p.68).





Davies and Mackenzie, 2014

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INCOSE

International Council on Systems Engineering

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https://www.flickr.com/photos/london2012oda/


European Roads
https://www.flickr.com/photos/chriszwolle/16162226070

What is the future of systems integration within civil infrastructure?

- Background
- Challenges
- State-of-art
- Opportunities
- Research agenda

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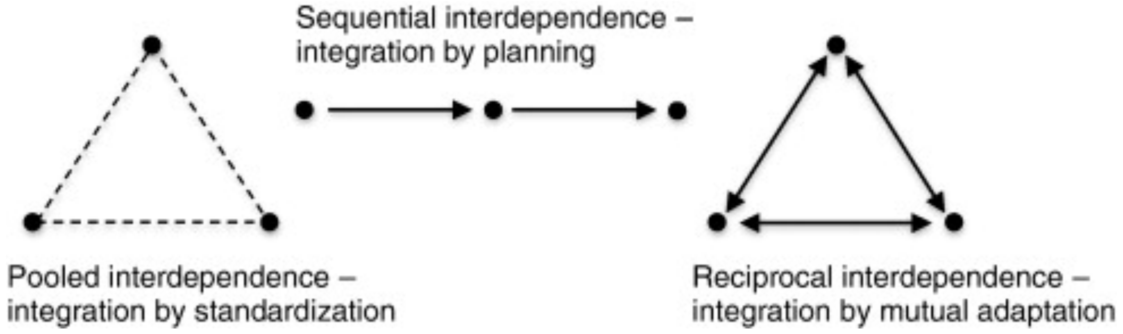
Background

Early history and theory of systems integration

- General theory of systems sketched out in the mid-20th century by Boulding (1956).
- Work in the 'Carnegie school' has been influential, particularly Simon (1981) on the *architecture* of complex systems
- Thompson (1967) on pooled, sequential and reciprocal *interdependence*.
- Scholars such as Perrow (1999 [1984]) start to describe organizations as tightly or loosely coupled systems.



Background

Early history and theory of systems integration

- In 1954 Ramo-Woodridge Corporation was employed as system integrator for the Atlas project (Hughes, 2000; Johnson, 1997; Morris, 2013), which developed ballistic missiles, with responsibility to: *"coordinate the work of hundreds of contractors and development of thousands of sub-systems"* (Mahnken, 2008: p.38).

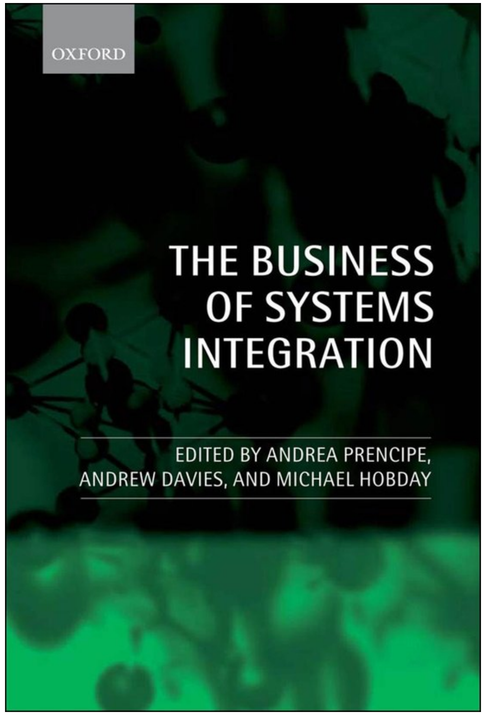
Additional organizational complexity across firm boundaries, contractors, supply-chains etc.

Background

Contemporary theory of systems integration

Systems integration as socio-technical:

1. Innovation studies: Firm acts as the 'systems integrator', capabilities of the firm, corporate strategy; characteristics of innovation in complex projects.



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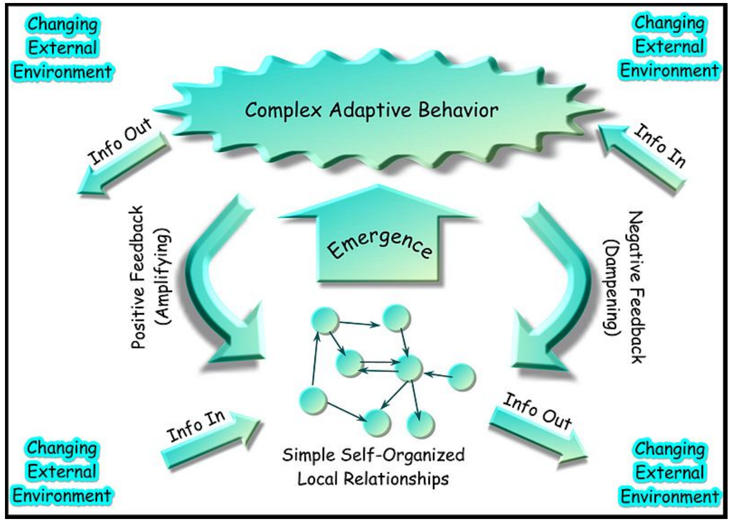
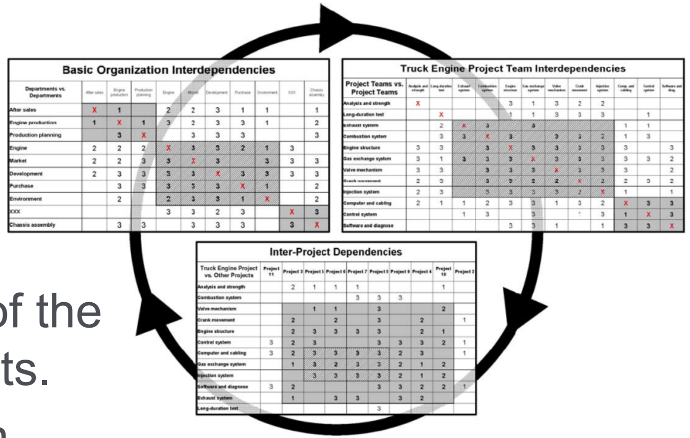


Background



Contemporary theory of systems integration

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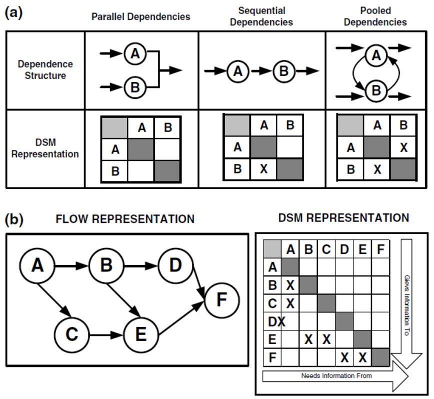
2. ***Complex projects***: Project complexity; inter-firm integration; integration across project stages; complex adaptive systems; governance; emergence.
3. ***Engineering design***: top-down approaches such as model-based systems engineering (MBSE); general theory of systems integration; and bottom-up approaches such as performance models and the Design Structure Matrix (DSM). System properties, such as risk, reliability, safety and resilience; direct and indirect interactions; verification and validation.



Danilovic and Sandkull, 2005

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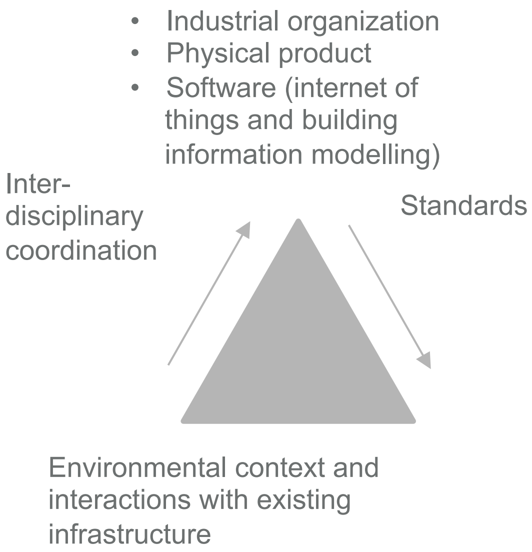
Questions: whether to standardize the interfaces or provide templates for processes? How to integrate software associated with complex projects?



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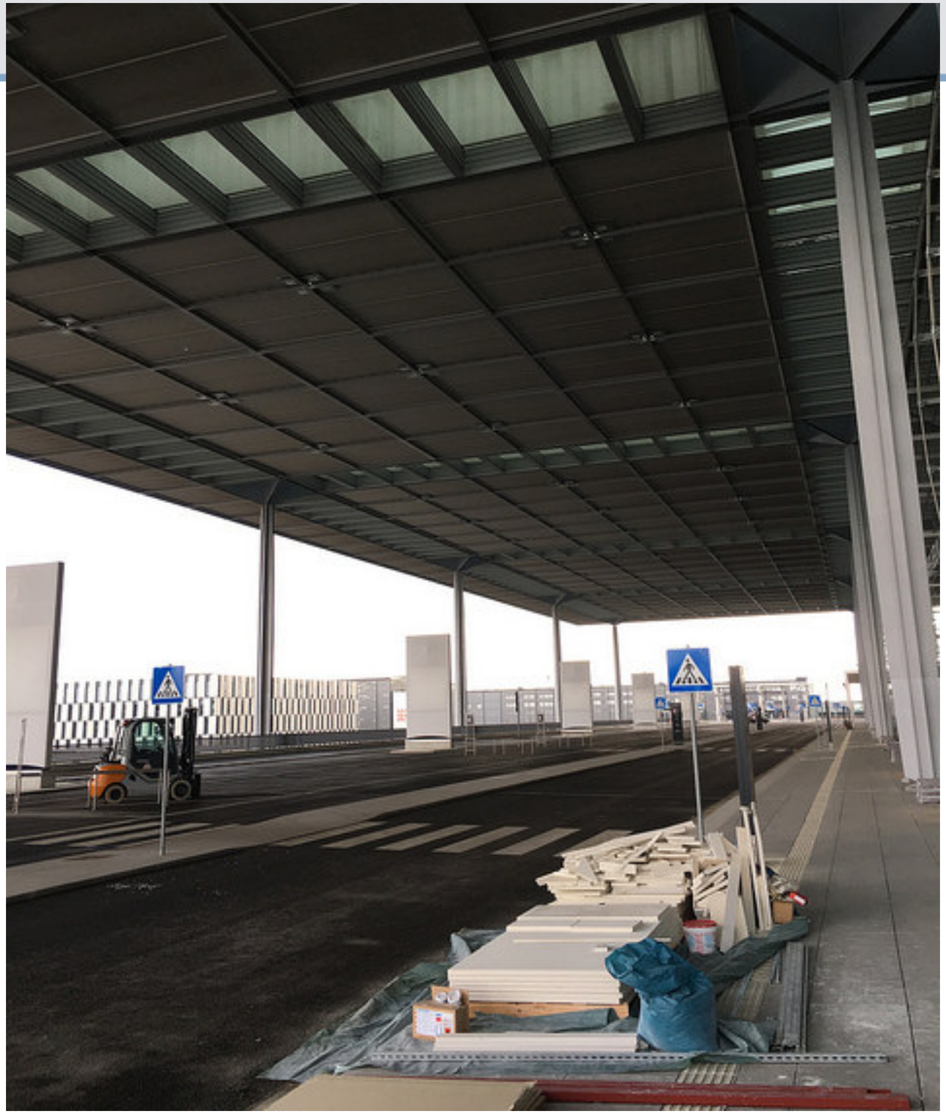
Challenges



John Worth, CC BY 2.0 https://www.flickr.com/photos/83015819@N00/22093720840/in/album-72157659604521819/

When components don't work together

- Already built, but not operational airport
- Originally planned to open in 2012, now planned to open in 2018 or 2019
- Initially found 20,000 issues to be addressed before opening (this later rose to 150,000 issues).
- Maintenance is €16 million per month

(Hammer, 2015)

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State-of-the-art research – policy and governance

Author	Contribution	Focus, methods and cases
Bouch (2015)	User-infrastructure interdependencies: research on new infrastructure business models (called iBUILD) including local business opportunities deriving from high-speed rail, proposing novel business models as 'enabler' in "complex, multiply-conflicting future city agendas."	Policy: MBSE, core modelling from infrastructure 2013 as a key policy document.
Davies and co-authors (Davies et al., 2009; Davies & MacKenzie, 2014; Geyer & Davies, 2000)	Drawing on innovation the strong tradition of work on complex projects that has examined the business of systems integration (Gann & Salter, 2000; Hobday et al., 2005; Prencipe, 2003) this work examines systems integration in infrastructure projects, contributing by.	Innovation studies, case studies: Heathrow Terminal 5; London 2012 Olympics.
Lundrigan et al. (2014)	Argues that megaprojects are organizations that are composed of other organizations (i.e. meta-organizations) and have two structures: a "core" that 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	Complex projects: London 2012 Olympics.
Miller (1997)	Optimization of project delivery and finance configuration at project and system levels based on analysis of more than 3000 infrastructure projects in the US and Hong Kong; detailed case of a multimodal transportation facility.	Finance: Large set of projects; USA transportation case.
Naderpajouh and Hastak (Naderpajouh, 2014; Naderpajouh & Hastak, 2014)	Modelled emergent dynamics and risks in institutionally complex projects (understood as systems of systems) that involve international organizations, public and community groups. Methodology proposed and applied to cases of social opposition in infrastructure: railway: Stuttgart 21; dams: Belo Monte Dam (Brazil), Bujagali Dam (Uganda); and pipelines: Keystone (N. America, Nabucco (Central Asia and Europe).	Policy: Mathematical model of risk based on theory of bargaining games. Examples focus on hydroelectric projects
Winch (1998)	Innovation systems and questions about the identification and role of the 'systems integrator' in construction.	Innovation studies: construction as a complex systems industry
Matar et al. (2015)	SySML model for sustainability in infrastructure involving 1) natural systems that make up an environment 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.	Infrastructure: MBSE using SySML modelling

State-of-the-art research – engineering systems integration

Author	Contribution	Focus, methods and cases
Baudains et al. (2014)	Approaches to examining ‘hidden’ connectivity by treating the building as a complex adaptive system.	Buildings: Review
Akanmu, Anumba and Messner (2012)	Cyber-physical integration through bi-directional coordination of virtual models and physical construction so changes in one are reflected in the other.	Buildings / virtual models: systems architecture and application scenarios
Geyer (2012)	Parametric systems modelling approach to sustainable building design, complementing IFC and gbXML standards that address information by seeking to represent multidisciplinary dependencies for performance-oriented planning, exploring the possible variations .physical–technical interdependencies, evaluation information, flows and behaviors.	Buildings: MBSE using SySML modelling as a basis for integrating design.
Shen et al. (2010)	Focus on integration of two or more construction software systems “to communicate, share or exchange information, and then to inter-operate in order to achieve a common objective.” This is considered from the perspective of data and frameworks interoperability.	Software: Review of research on construction software integration
Tao (2000)	Asset management model and systems integration approach to integrate asset management of components at different stages of their development life cycles. Business, system requirements, logical design, physical design, development and implementation considered to ensure interoperability and effective asset management.	Data: Developed asset management model and operational scenario tool.
Zhu and Mostafavi (2015)	Prospective identification of vulnerability to uncertainty through analysis of construction projects as networks. Uncertain events impact through perturbation of nodes (humans, information, resource and task) and their links, changing topological structure with negative effects on project efficiency. Extent of variation is used to indicate vulnerability across different event scenarios.	Resilience: Dynamic network analysis and Monte Carlo simulation; worked example of a tunnelling project.

State-of-the-art research – main extant tools

Tools, techniques and approaches	Focus and uses
From the general research on systems integration	
General theory of systems integration (GTSI)	Systems consist of objects and processes that have non-reciprocal emergence. An object has mechanisms that have logic structures, enacted in processes involving energy, matter, material wealth and information (EMMI). Interactions between objects may lead to stable or metastable objects; and take place through EMMI creating constraints on objects, which change their boundaries and boundary conditions precipitating emergence (Langford, 2011, 2013). General equations are used to calculate systems properties and loss.
Design Structure Matrix (DSM)	A matrix used to consider the interdependencies between different components of the process in order to sequence design activities, or of the product in order to understand ex-ante components with high levels of interdependence and to cluster these (Austin, 2001; Eppinger & Browning, 2012; Steward, 1981).
System theoretic accident model (STAMP)	Treats accidents as a chain of events rather than seeking root causes, and sees reliability and safety as different properties of systems, developed by Leveson (2011) .

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State-of-the-art research – main extant tools

Tools, techniques and approaches	Focus and uses
Used in relation to civil infrastructure	
SysML	Using the Model Based Systems Engineering (MBSE), SysML is a modelling language based on UML that can be used to describe systems and their interconnections. It has been used in research on integrated and sustainable design in buildings (Geyer, 2012) and infrastructure (Matar et al., 2015).
Systems dynamics	This approach is used in understanding the dynamics of management in complex projects (Lyneis, Cooper, & Els, 2001); and for understanding error propagation and rework (Love, Edwards, Irani, & Goh, 2011).
Network analysis	A post-facto tool, which is beginning to be used along with Monte Carlo simulation for ex-ante prediction. Software tools such as UCINet and Gephi are used in social network analysis (SNA), with other programming tools such as igraph, which can be programmed in r language and python, and can take data from pajek. Recent work has used SNA to examine the heterogeneous networks involved in projects and their dynamics (Guo, 2015; Zhu & Mostafavi, 2015). There is an opportunity to link this understanding with performance.
Montecarlo simulation	This is used by Zhu and Mostafavi (2015) to get probabilities of different outcomes occurring, with respect to the perturbations of a defined network. Unlike the DSM, this approach cannot consider the case where it would be possible to change the shape of the network, but can provide information about the resilience of a given network to particular types of events.
Scenario planning	An operational scenario tool proposed as part of the implementation strategy for asset management (Tao et al., 2000).

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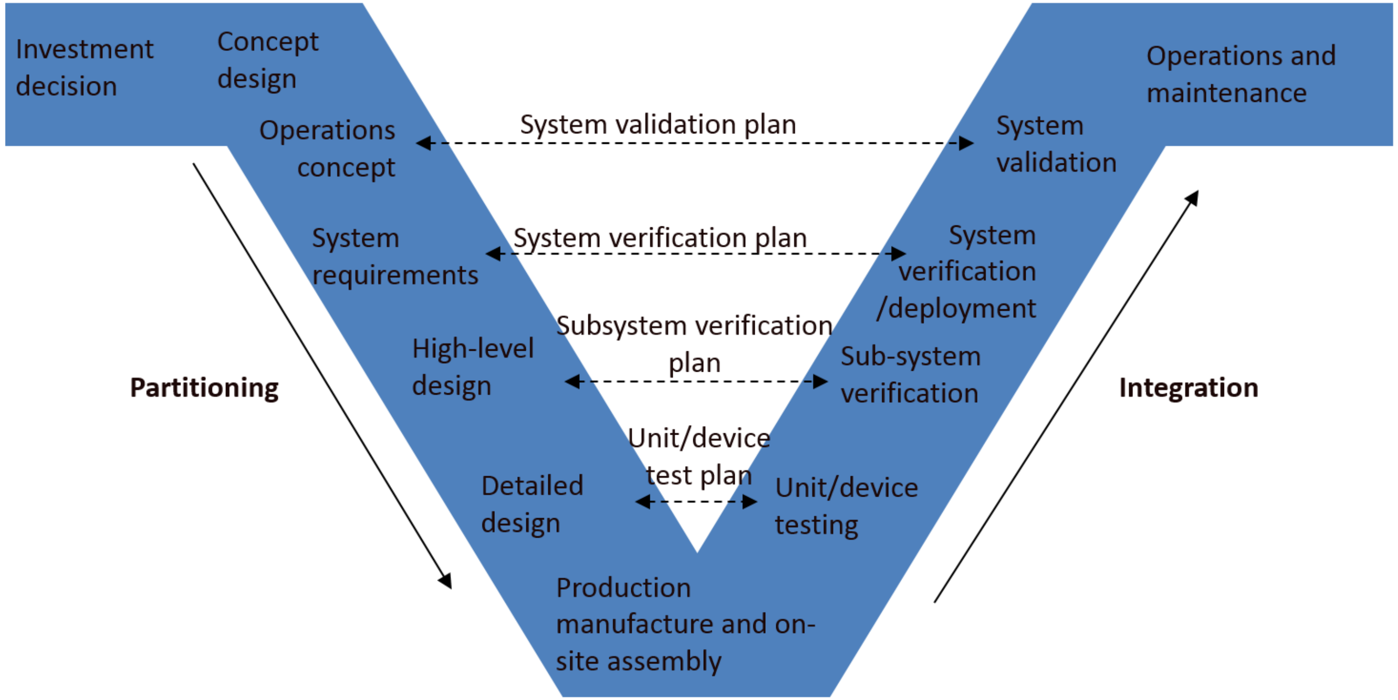
Opportunities



- From projects to systems and systems of systems
- Using the potential of new forms of data analytics
- Towards next-generation tools and approaches

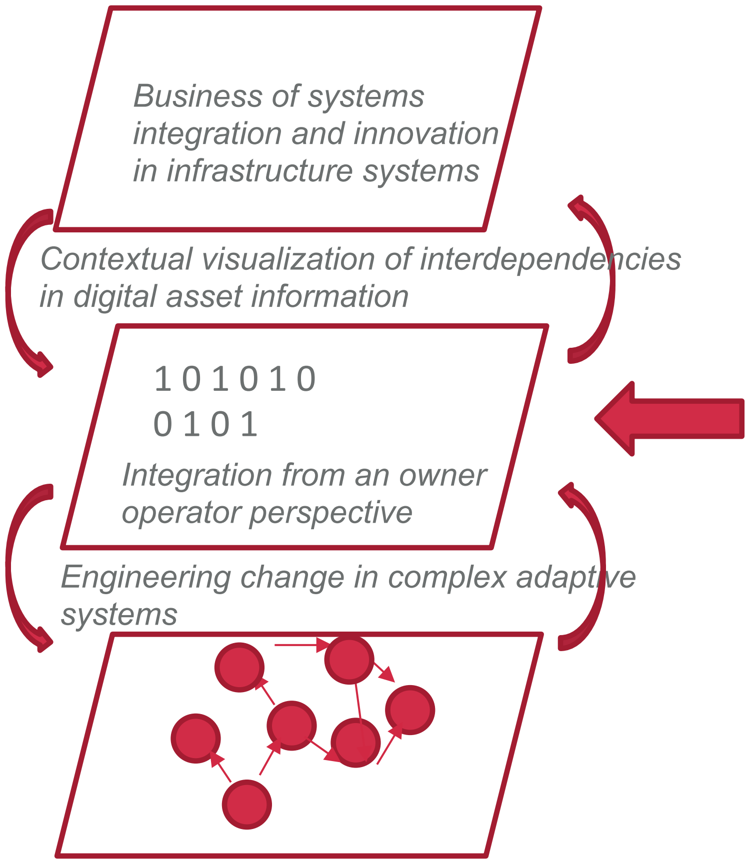
Research Agenda - People, IT and concrete

Mapping processes

Work and production systems

Digital interfaces

Cyber-physical infrastructure



Drawing lessons from other sectors: MBSE, DSM, STAMP etc from other industries

Research Agenda

To visualize and understand civil infrastructure as a complex product system, with enabling production and work systems to enables a move from retrospective to prospective visualization of interconnections, interactions, interdependencies.

1. Take recent theory of, and latest tools for, systems integration (e.g. GTSI, STAMP, DSM); applying them to construction context and assessing the results.
2. Map the dynamics of systems integration decisions in different infrastructure sectors (e.g. using social network analysis; Monte Carlo simulation).
3. New approaches using a range of machine learning, graph theory, systems dynamics and scenario planning techniques to develop a new generation of tools and processes for systems integration that use data analytics to visualize and understand relationships between parts and the systemic consequences of changes in complex product systems.

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