Using Digital Twins for Managing Change in Complex Projects

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Abstract. Complex systems are not entirely decomposable; hence, interdependencies arise at the interfaces in complex projects. When changes occur, significant risks arise at these interfaces as it is hard to identify, manage and visualise the systemic consequences of changes. Particularly problematic are the interfaces in which there are multiple interdependencies, which occur where the boundaries between design components, contracts and organisation coincide, such as between design disciplines. In this paper, we propose an approach to digital twin-based interface management, through an underpinning state-of-the-art review of the existing technical literature and a research agenda to identify the characteristics of future data-driven solutions. We set out an approach to digital twin-based interface management and an agenda for research on advanced methodologies for managing change in complex projects. This agenda includes the need to integrate work on identifying systems interfaces, change propagation and visualisation, and the potential to significantly extend the limitations of existing solutions by using developments in the digital twin, such as linked data, semantic enrichment, network analyses, natural language processing (NLP)-enhanced ontology and machine learning.

Keywords: Managing change · interface management · digital twin · semantic enrichment

1 Introduction

Complex projects arise in sectors such as infrastructure, new energy and resources. Systems integration challenges are a significant problem [1, 2]. Yet, there is the potential for advanced digital methods to provide information to engineers and decision-makers that is needed to better manage these changes [3, 4]. This is important as complex projects are increasingly delivering cyber-physical systems as interventions into existing natural

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as well as built environments. As the number of internal and external interfaces grows, new systems integration challenges emerge [5]. These challenges are particularly salient when late changes are made to designs: even internationally leading engineering firms can find addressing these challenges as they might have unrecognised systemic impacts [4]. Hence, this paper provides an underpinning state of the art of the existing literature and a research agenda to identify the characteristics of future solutions and opportunities for research.

2 Theoretical Background and State-of-the-Art

We build on work to conceptualise and model interdependent large-scale infrastructure systems [6], and to understand the propagation of changes within them [7]. Engineering change has been described as a six-step process, as shown in Fig. 1. In practice, we have found that steps 2 and 3 are not well undertaken, and typically consider a very limited range of factors, with potential impacts of the change emergent in stage 6, rather than ahead of the approval of the change.

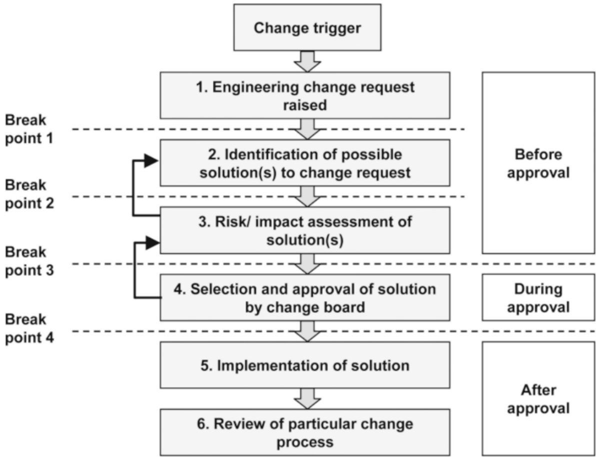

Fig. 1. The Engineering Change process, from Hamraz, Caldwell and Clarkson [8], who adapts from Jarratt, Clarkson and Eckert [9]

In complex projects, this process is particularly challenging as major technical interface challenges arise across different engineering disciplines and organisational boundaries, e.g. where accountability and responsibility become unclear, and changes in architecture result from emerging complexities and uncertainties (e.g. between systems with mature and novel technologies projects [1]).

2.1 Systems Approaches

From a systems perspective, managing engineering change is related to the overall architecture as it forms a step in a configuration management process [10]. It is particularly associated with configuration control, where all changes to configuration items are controlled to ensure the integrity of the overall system. Such techniques, developed in safety-critical sectors such as nuclear and defence, provide a robust framework for managing engineering systems through their design, delivery and operation.

This systems approach recognises the different degrees of modularity of different architectures, which will create more or less complexity to be managed through a change process, and more or less potential for innovation [11]. One area of concern should be to reduce complexity at the outset, and another to manage the interfaces where interdependencies persist, so engineering changes can be understood and their impacts controlled.

2.2 Managing Change

Managing design change, within the wider frameworks, requires the identification of systems interfaces, analyses of change propagation across these and visualisation of outcomes for decision makers. In complex projects, substantial work proceeds through the use of the Design Structure Matrix (DSM) [12] (Also known as an N2 Interface Matrix) as a tool to identify the impacts of change in large engineering designs, using geometric data on connections between components [13] and process data on co-viewing of different aspects of design [14] with unrealised opportunities to combine these approaches. This interdependence across interfaces can relate to physical connections, energy, mass and information flows [15].

Efforts to analyse and minimise the impact of design changes have been the subject of many studies. One notable theoretical framework is the "patching" proposed by Eastman, Parker and Jeng [16]. Patching is an action that modifies a design as locally as possible to minimise impact while maintaining global integrity with the rest of the design. A range of manual and analytic approaches have been developed, including the application of probabilistic methods to a network of dependencies [7][1].

2.3 Developments in the Digital Twin

While most work has been on digital twins in operations, recent research advances an emerging area of work on their use in design and construction [17, 18]. Research on the digital twin in construction is underpinned by standard ways to describe data [19]. Within the field of research on AI and design [20, 21], different approaches to identifying these engineering interfaces are emerging.

Link and display heterogeneous data-sets to enable decision-making, with existing work focused on constraints in scheduling data [22], and the visualisation of requirements and outcomes in dashboards and indicators, for example, in a construction production control room [23], and the potential for extension to support an 'interface digital twin'.

[1] More details can be found in [2402.00325] Using digital twins for managing change in complex projects (arxiv.org).

2.4 New Areas

Growing challenges of sustainability and resilience are increasing the extent to which engineering systems, delivered through complex projects, need to be seen as open rather than closed systems. Much of the work on managing change has focused internally within the project boundaries. At the same time, significant advances have been made in recent years with a focus on modelling at the national and regional level, with relatively little connection to the project level. Yet, to tackle systemic issues such as resilience, new approaches are needed to understand external as well as internal interdependencies in ways that inform decisions on projects.

3 Research Agenda for Digital Twin-Based Interface Management

We anticipate an approach to digital twin-based interface management that extracts design information from information models, evaluates interfaces and interdependencies in complex systems, automates methods and integrates and visualises the outputs to enable proactive decision-making and validate the approach.

On complex projects, the number of interfaces and interdependencies can be very large, and there are opportunities to use graphs of these as a scalable non-tabular database solution. There is a need for a method for the generation of interface knowledge graphs that enable the identification of interfaces between physical, contractual and organisational systems in infrastructure design. Sources of information are BIM models, product and work breakdown structures, drawings, meeting minutes and other available engineering design and construction materials. Missing information on interfaces can be identified through an NLP-enabled ontology of interfaces, BIM log mining and graph inferencing. In doing so, BIM log mining [24] and NLP on process knowledge [25] are used to generate an enriched interface knowledge graph with knowledge of interface relations from both design and process data. Additionally, we also leverage graph-based inferencing on data from the specific case to infer missing connections in the interface knowledge graph and identify graph vulnerabilities.

To address the potential for change scenarios in the design interdependencies there is a need for generating risk-informed knowledge graphs, namely *risk register knowledge graph*. Risk registers are the core artifacts culminated from tacit and explicit knowledge associated with risk [26]. Connecting the knowledge interface with risk registers provides a feedback mechanism between the risk register and the interface knowledge graph (from) to suggest the potential for reducing complexity and design flexibility based on potential risks [27]. Such risks can be associated with the operation or design of interdependent infrastructure systems [6]. The feedback mechanism provides a more comprehensive understanding across both knowledge domains by (i) informing risk registers from the interface knowledge graph that connects physical, contractual and organisational interfaces, (ii) informing the interface knowledge graph by the textual and quantitative information associated with risk registers. As a result, there is a chance to prioritise changes and allow design flexibility (as framed by Cardin, Ka-Ho Yue, Jiang, Deng and Santhanakrishnan [28]) through a risk-informed decision-making process.

Next, the *interface knowledge graphs* and *risk register knowledge graph* are integrated. An illustration of the relationship between the interface knowledge graph and the risk-informed interface knowledge graph is shown in Fig. 2. Manual integration will be followed by automated methods such as automated ontology alignment using semantic and structural embeddings of knowledge graphs [29]. This integration is critical as risks in complex systems are dynamic during the changes in the design interdependencies. Therefore, the layer of information about potential risk scenarios from the risk register knowledge graph combined with the interdependencies from the interface knowledge graph will help identify and manage emerging risks from design changes. Design flexibility is also enabled through the use of causality in selected knowledge graphs to identify change propagation [30].

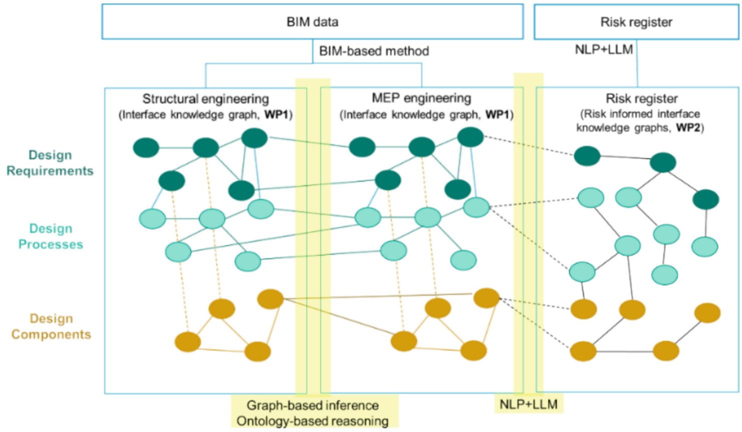

Fig. 2. The relationship between interface knowledge graph and risk-informed interface knowledge graph.

There is a need for a methodology for automating the extraction and augmentation of BIM data on systems interdependencies. The aim is to enable proactive decision-making by using semantic enrichment and automation in the identification of interfaces, interdependencies and risks in the components and systems architecture of a new project. Potential interface issues and critical changes in projects requiring attention will be highlighted by comparing the graph representations with knowledge graphs, enabling System integration and visualisation to further analyse interdependencies of interface issues to inform decision making.

Graphs of interdependencies are not readable to engineers and managers, and hence interpreting the information to inform decision-making is important. The development of advanced visual methods to make information 'human-readable' to decision-makers is crucial to enable the rapid and proactive use of our digital twin-based interface management methods in project decision-making. The dashboards and indicators developed for the interface management methods aforementioned aim to operate like a search tool for engineering design data, enabling an 'interface digital twin', with information in a digital twin representation that attracts engineers' and designers' attention to the areas of most likely concern in a system configuration.

These methods developed in the lab can be validated through industry trials and benchmarking, allowing engineers and designers to engage directly with the tool, and also get their feedback on pathways to impact and the potential for collaborating to extend this basic research to develop practical use cases in areas of current need (e.g. water, housing and energy).

4 Conclusion

We set out an approach to digital twin-based interface management and an agenda for research on advanced methodologies for managing change in complex projects. Recent developments in the digital twin make possible a new generation of techniques for managing change on complex projects. This is important because the scale and complexity of construction and infrastructure projects are growing, and we are becoming more aware of their interfaces and interdependencies, within the project and across project boundaries. The contribution of this paper is to identify opportunities to combine digital-twin-based methods with advances, e.g. in linked data, ML and semantic enrichment, to significantly advance the ability to address interdependencies at interfaces in complex projects.

The agenda we set out includes the need to integrate work on identifying systems interfaces, change propagation and visualisation, and the potential to significantly extend the limitations of existing solutions by using developments in the digital twin, such as linked data, semantic enrichment, network analyses, natural language processing (NLP)-enhanced ontology and machine learning.

We suggest some directions for future research. For example, scholars of BIM and digital twins can build on this work to develop methods to integrate the learnings on interface as suggestions into design phase models helping the creation of interface knowledge graphs for future projects. This would be an essential step for distributed models in the infrastructure and modularise design processes in complex projects. Scholars of change management can build on this work [31], both to develop new network-based approaches that extend existing matrix methods (such as the DSM) and also to address the significant opportunities to develop a better ex-ante understanding of interfaces and interdependencies within projects (internal interfaces between systems and components) and across their boundaries (addressing larger-scale issues of resilience). Scholars of project management and design can use such methods to improve the flexibility of design in complex projects, where there are emergent complexities as well as those identified at the outset where technologies are developing at different rates, for example in airport projects, where baggage handling systems are updated on relatively short timescales, such that it is important to understand interdependencies in order to leave flexibility in the design to accommodate new systems.

The new approaches we outline provide methods for engaging with large-scale, heterogeneous data, to understand the systemic consequences of changes and enable better real-time decisions on projects. New research can develop approaches to use emerging techniques to better manage risks across portfolios and programs of projects.

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