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DEVISING AND IMPLEMENTING PROCESS MODELS WITHIN INFRASTRUCTURE ENGINEERING DESIGN

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ABSTRACT

A plethora of process models have been developed over the years with the aim to improve the performance of design and construction processes. However, effective adoption of process models is still limited; lack of guidance on which model type would be applicable in the given contexts, and an excessive focus on the design of the process models themselves instead of their implementation may be some of the reasons for this. This research investigates how process models should be used within infrastructure engineering design, considering also how different methods suit different purposes. Findings from an ongoing research project in the UK are presented, following case study as its research strategy. This paper reviews the use of process models and clarifies their relationships by describing the adopted models and comparing them with the models explored in the literature, increasing the understanding of process models within infrastructure engineering design. Benefits, limitations and challenges are also discussed, supporting future applications.

KEYWORDS

Lean Design, Infrastructure, Process Models, Value Stream Mapping, Ji Koutei Kanketsu

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INTRODUCTION

Difficulties in managing the design in construction are a consequence of the complex nature of the process, as decisions need to be made in an uncertain environment (Ballard and Koskela 1998). Moreover, there are many factors that often push the design process away from the optimal design sequence, e.g. internal and external uncertainty, resulting in extended durations, low productivity and decreased quality of the design solution (Koskela et al, 1997). Thus, design processes are especially challenging to manage and navigate when compared with other processes, such as construction or manufacturing, as they tend to involve aspects of iteration, novelty and complexity to a great extent (Wynn and Clarkson 2018).

In this context, it has been recommended that development and improvement of process models can help to navigate and address those challenges in several ways (Cooper and Kagioglou 1998; Wynn and Clarkson 2018). Several methods for the analysis of business operations depend on representation known as business process models (Dumas et al. 2009), which are the combination of a set of tasks with a structure describing their logical sequence and dependence, aiming to produce a desired output (Aguilar-Savén 2004). However, no single model can address all the issues, as it involves taking into account the purpose of the analysis or uses of the models, and the knowledge of existing modelling techniques (Aguilar-Savén 2004; Wynn and Clarkson 2018). Further research is needed to investigate how models can be most effective. Thus, the aim of this paper is to increase the understanding of process models within infrastructure engineering design and clarifies their relationship by comparing them with the models explored in the literature. The contribution is related to the guidance on how process models should be used in civil engineering projects, considering different purposes.

DESIGN PROCESS MODELLING

INTRODUCTION

Even though the design process involves novelty, complexity and iterations, it also contains routine sequences and structures that can be modelled (Wynn and Clarkson 2018). Process models may be beneficial to reduce the possibility of missing an important step, allow design to be transferred and coordinated, enable planning, improve communication among disciplines, and generate or communicate conceptual insights (Gericke and Blessing 2011; Wynn and Clarkson 2018). It can also support standardisation, improvements, and optimisation of processes. Different definitions of processes can be found in the literature, and there has been an evolving debate about these definitions (Tzortzopoulos et al. 2005).

Two main process model types used for understanding, organising, and improving the work and information flows are described in the literature as 'as-is' and 'to-be'. The 'as-is' model, also described as true maps of what happens, can provide a clear understanding and description of the current state using a descriptive approach, whereas the 'to-be' model, also called as potential maps of what ought to happen, prescribes an action for improvement; and it is argued that both models are required (Tzortzopoulos et al. 2005). Models can also present different levels of process detail. They are described as: (i) generic or high-level maps, which can provide an overview of the entire process, including the key stages or sequences, the information flow between different actors, deliverables and stage reviews (Cooper and Kagioglou 1998; Tzortzopoulos et al. 2005); and (ii) detailed maps, which usually adopt structured modelling approaches (Sanvido

1990), focusing on information flows. Recent studies also refer to other key elements that can be measured to analyse the information flow in design, such as batch sizes, flow bottlenecks, and work in progress (WIP) inventories (Tribelsky and Sacks 2011). The process maturity is often recognised as: (i) initial processes; (ii) repeatable processes; (iii) standardised processes; (iv) measured and controlled processes; and (v) optimised process (Macintosh 1993). Levels one to three are associated with describing the process, whereas levels four and five are related to decision support to monitor the process (Aguilar-Savén 2004).

The sections below introduce commonly used design process modelling techniques, such as swim-lane, Value Stream Mapping (VSM), and Ji Koutei Kanketsu (JKK).

COMMONLY USED DESIGN PROCESS MODELLING TECHNIQUES

There are plenty of business process modelling techniques, and the most frequently used are identified as: flow chart, data flow diagrams, role activity or interaction diagrams, Gantt chart, business process modelling notation (BPMN), workflow technique and swim-lane, also called as cross-functional diagram (Aguilar-Savén 2004; Jeyaraj et al. 2014). Swim-lane diagrams are considered to be a primary modelling technique when assessing business procedures and rules as they convey information to stakeholders, especially when they include important visual signs, as well as collaborative and decision making activities (Jeyaraj et al. 2014). They help in visualising the flow of information, identifying how the information is exchanged among stakeholders, and highlighting the information deliverables (Al Hattab and Hamzeh 2013). Swim-lane differs from other diagrams in that it can consider user roles for the workflow, assigning activities or boxes to specific user groups, and it can include criteria to define which activity comes next if various activities are available, defining the sequence of activities (Jeyaraj et al. 2014). Design and construction efforts in lean projects start with collaborative process modelling, in order to create a common understanding of the process among all stakeholders and to enable the teams to identify and analyse waste (Chiu and Cousins 2020). Swim-lane is one of the techniques adopted in the collaborative process (Chiu and Cousins 2020), and usually each lane represents a function or discipline, and a timescale is considered as columns, in order to develop an achievable time-lined plan for the project.

VALUE STREAM MAPPING

Value stream mapping (VSM) is a technique that can help companies to identify long lead times, non-adding value activities, bottlenecks and other wastes, and then address the root causes (Rother and Shook 2003). VSM can provide a road map for process improvement, as it compares current (as-is) and potential future states (to-be) (Arbulu et al. 2003). This technique can help understand the flow of information and materials as a product progresses through the value stream (Rother and Shook 2003). A value stream map follows a product's production journey from the start to the end, i.e. customer to supplier, and visually represents every step in the information and material flow (Rother and Shook 2003). It can also look across individual functions, activities, departments and organizations and focus on overall system performance (Arbulu et al. 2003).Thus, VSM proposes a holistic perspective of how the work flows through the whole system. It can be carried out in three key steps, i.e. identifying and organising the process tasks and information flows, collecting performance data, and assessing how value is created (Mcmanus 2005). Martin and Osterling (2014) describe the key benefits of VSM, such as: (i) it provides means to establish a strategic approach for improvements through various degrees of granularity; (ii) it provides a highly visual perspective of the full cycle, its components and cross-functional work systems; (iii) it deepens the understanding of value adding activities and their delivery; and (iv) it provides data-driven decision making. This technique can be used to support important processes in product development (Wynn and Clarkson 2018). However, the VSM concepts need to be adapted from manufacturing to construction, e.g. defining the specific element to be investigated and the unit of analysis (Rosenbaum et al. 2014), and this can be considered a challenge. The time spent to collect the current state data can also create difficulties associated with the continuous use of VSM (Forno et al. 2014)

JI KOUTEI KANKETSU

Ji Koutei Kanketsu (JKK), which means 'complete your own process' in Japanese, is based on the fundamental concept of '*jidoka*' and tailored for non-production departments, which mostly deal with intangible products such as information (Manabe and Heller 2014). The JKK focus is the 'individual', which is frequently neglected in the whole management process. JKK is considered a process design method that designs and arranges activities in suitable order, simultaneously attaching the necessary conditions and judgement criteria to those activities (Manabe and Heller 2014). JKK's process model supports the individual to understand the whole process where their activities are embedded. The process model is normally presented in the Work Process Flow Chart, within which the process is described clearly and detailed from start to end (Manabe and Heller 2014). The implementation of JKK does not end at developing an overall process flow chart; in fact, its implementation comprises the adoption of all JKK's focal elements: (1) work purpose/target, (2) work processes, (3) necessary conditions, (4) judgement criteria, and the implementation of PDCA in daily work. After understanding the work purpose/target, and work processes, the individual continues to identify their own activities within the process and breaks them down into work units, down to the smallest element where one can make their own decision (Manabe and Heller 2014). Continuously, the two JKK's focal elements -necessary conditions and judgement criteria- should be attached to each work unit. The purpose of having these two elements for each work unit is to help the individual avoid producing defective outputs due to a lack of work required conditions, and to operate self-assessment of their own works.

RESEARCH METHOD

An empirical case study was carried out at an infrastructure design and consultancy company in the UK as part of a Knowledge Transfer Partnership (KTP) project. KTP is a partially government-funded programme, sponsored by InnovateUK, to encourage collaboration between academia and industry, and this project is exploring the integration of Lean and digital design. A case study explores a contemporary event in depth and within its environment, particularly when the boundaries between the event and context are not clearly defined (Yin 1994). The research consisted of the development and critical analysis of the process modelling methods adopted by the company. The investigation is limited to highways construction projects.

The study was conducted in four stages: (i) overall process modelling of all disciplines, carried out by the research team in collaboration with company staff; (ii) discipline specific, BIM and digital process modelling, developed by the research, design and BIM team members; (iii) VSM of selected disciplines and projects, carried out by the research team and an external consultant in collaboration with team members; (iv) JKK implementation on a design process developed by the research team in collaboration with company staff; and (v) analysis and reflection on the theorical and practical contributions. The processes were selected through a top-down approach, identifying relevant processes to the company, i.e. projects that characterise a significant portion of the business and interface with various disciplines, as well as processes that are carried out through informal and inconsistent approaches, with no clear definition of responsibilities and sequence of activities, such as the clash management BIM process. The main sources of evidence are: (i) open interviews with the design discipline leads to develop the overall process modelling; (ii) workshops with the design and BIM team members to develop the process models; (iii) workshops with key stakeholders to validate and present the process models developed; (iv) analysis of design documents and existing protocols; and (v) iterative cycles of reviews with the research team, external consultant and key stakeholders.

DESCRIPTION OF THE PROCESS MODELS ADOPTED IN THE COMPANY

The starting point of the process modelling activities was the overall process modelling of all disciplines (Figure 1), aiming to identify key interfaces and interdependencies among all disciplines involved in the design process. The company and the research team realised that a more detailed process map for each discipline (Figure 2) was required in order to identify the stakeholders involved, as well as the opportunities for improvement. The use of Lean techniques, such as detailed swim-lane, VSM and JKK, to map subprocess (Figure 3, Figure 4 and Figure 5) emerged as a necessity to better understand the necessary conditions and judgment criteria of each activity, as well as clarify the responsibilities, requirements and resources.

OVERALL PROCESS MODELLING

The focus of the process modelling exercise was to achieve a comprehensive understanding of the current BIM-based design processes, the interconnections between multiple disciplines and waste. This was the initial step in the company's effort in improving the design process performance. The BIM-based design process map was created through interviews with the design leads from various disciplines, which were a combination of face-to-face and online meetings. The company desired to examine all 17 disciplines involved in this practice; however, only 13 disciplines were assessed and mapped (Figure 1). The practice started by mapping activities for individual processes of the seventeen design disciplines, such as highways design, structures, and drainage. Then, individual processes were linked together to create a synthetic process diagram by connecting their shared activities. Beside the need to present a series of process steps, the design disciplines were also the central feature of the map, which led to the selection of a swim-lane diagram for this practice. The key benefit expected was associated with building an understanding between the cross functional discipline areas.

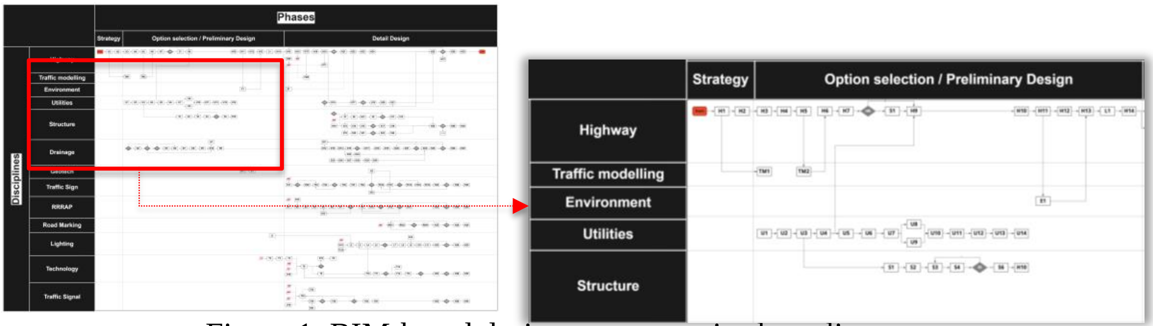

Figure 1. BIM-based design process swim-lane diagram.

Through the modelling practice, the company discovered several existing issues within the current design process including (i) rework, (ii) redundant activities and (iii) lack of input when starting of activities. Rework regularly happened due to the deployment of activities in various disciplines without having adequate input information and all the necessary conditions in place. Lack of awareness of which activities can be automatically carried out led to the occurrence of redundant activities. The involvement of multiple design disciplines caused numerous challenges for the process mapping, including (i) the difficulty in choosing appropriate design leads who have an in-depth comprehension of their own works, (ii) the time consumed while linking all individual processes into a synthetic process, (iii) laborious reviewing of the process maps, and (iv) the massive size of the diagram, creating barriers for its implementation and practical use.

DISCIPLINE SPECIFIC PROCESS MODELLING

The design discipline specific process models (Figure 2) were introduced as a countermeasure to the difficulties identified within the overall process modelling, identifying the key stakeholders, and opportunities for improvement within specific activities. The improvements were mostly related to early involvement of the internal and external stakeholders, checking and coordination activities, standardisation and automation of the design activities. It consisted in the following steps: (i) developing a process map based on previous experience and in collaboration with the key stakeholders, such as the discipline leads; (ii) validating with the team members through workshops; (iii) testing the process in a trial project with similar characteristics; (iv) identifying, analysing, planning and implementing the improvement opportunities, aiming to remove waste and generate value for the client; and finally (v) capturing, measuring and monitoring the benefits realised. It followed the same approach as the overall process modelling, i.e. swim-lane diagram, as the stakeholders and the key design phases had a central role in the model. The digital platform Miro (https://miro.com/) was adopted to support the initial and collaborative discussions regarding the identification and sequencing of activities. As soon as a process was agreed and validated with the team members, the information was transferred from to Microsoft Visio, aiming to connect it with the company intranet. The company mandated for all design discipline specific processes to be owned and developed by each community of practice and discipline leads, with the support of the Lean and digital team, in order to identify improvement opportunities and wastage.

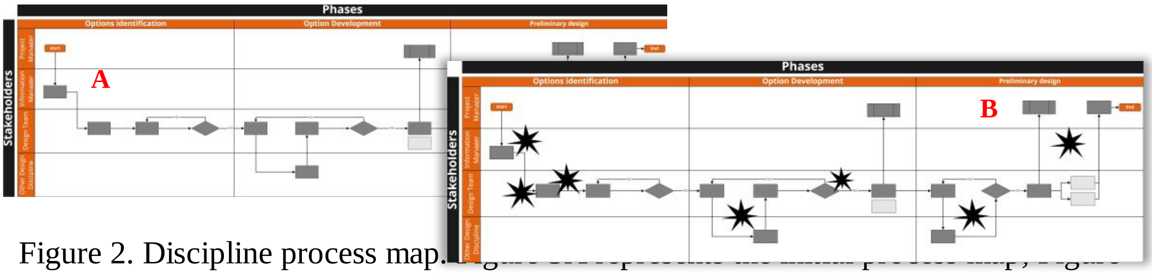

Figure 2. Discipline process map. Figure 3A represents the initial process map; Figure 3B, the improvement opportunities identified.

The key benefits realised from this modelling exercise were related to the visualisation of the process, creation of standard models with the potential to implement on similar projects, adoption of the model as a blue-print, training and educational tool for new staff. These can lead to the reduction of procedural errors, identification of missing activities in the current practices and understanding the complexity and interaction within the activities. The key challenges of this exercise were related to the lack of availability of the disciplines to engage in the mapping, reviewing and testing of the process map, as well as difficulties in implementing the process model itself.

BIM AND DIGITAL SUB-PROCESS MODELLING

BIM and digital sub-processes were the third level of the process analysis. The aim of this practice was to detail a key process, i.e. clash management (Figure 3), formalise the key steps and provide visual information of the process, as there is still a gap in its formalisation (Pedo et al. 2021). Most research considers only the software tools instead of the process elements (Pedo et al. 2021), leaving the resources, activity flows, and underlying purposes at a marginal level. The process modelling was also aligned with the overall BIM process maps developed by the company and with the ISO 19650 recommendations. The process modelling approach was very similar with the one adopted for the discipline-specific modelling, however, it was focused on the information flow. The activities were identified through workshops with the design and BIM leads and document analysis. The clash management process mapping exercise was restricted to highway design projects, however, the processes adopted in other projects within the company present a degree of similarity in key activities, which allows the standardisation of the model for other projects. The key challenges of this practice were related to the engagement of the BIM team to test and implement the process mapped within other projects, as well as to the capturing of efforts spent in the process.

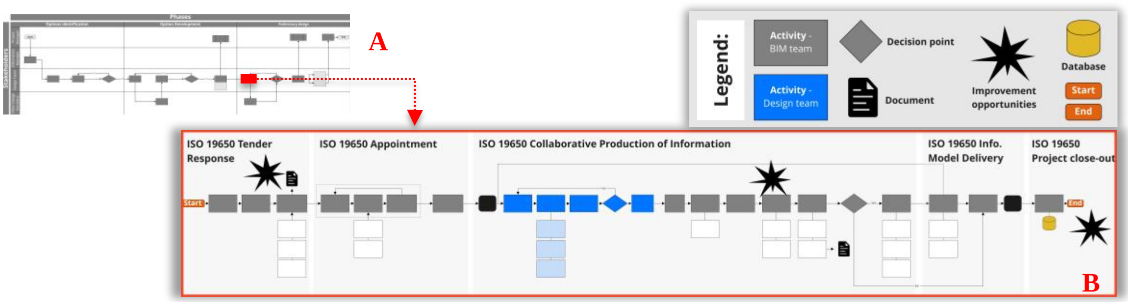

Figure 3. Clash Management process map. Figure 4A represents the BIM subprocess identified within the discipline process map; Figure 4B, clash management map itself.

VSM OF KEY DESIGN PROCESSES

VSM was adopted to capture a 'current state' and potential 'future states', illustrating opportunities for improvement. A steel bridge design process was value stream mapped as a pilot exercise. The VSM (Figure 4) was developed through workshops in collaboration with the bridge design team, the research team and an external Lean consultant, who led this initiative for the company. The starting point was the development of the current state, or as-is process, illustrating how the bridge is currently designed. The VSM was formed according to the key bridge design elements, such as initial assessment, pile design, beam design, substructure design, superstructure design, and review, represented in different lanes. The key process components contained in the VSM were the activities, resource required (number of stakeholders involved), cycle time, and waiting times in between boxes.

The current state map served as the basis for developing future state maps that would eliminate or reduce unnecessary steps, waiting times and interfaces. Issues and improvement opportunities were identified through discussions with the key discipline team members, supporting the design of the future states. Three different scenarios for future states were defined: (i) improved state (short-term improvements), (ii) ideal state (medium or long-term improvements), and (iii) perfect future state (perfect process with no waste). The team started developing the short-term improvements, following the medium-term improvements, but always aiming for the perfect future state. The challenges of this practice were mostly in implementing the future states, especially the resistance to change, and consequently, the lack of engagement from the designers. Another challenge was associated with the different types of bridges, thus, the VSM of one bridge was not replicable to all the bridge design currently ongoing within the company.

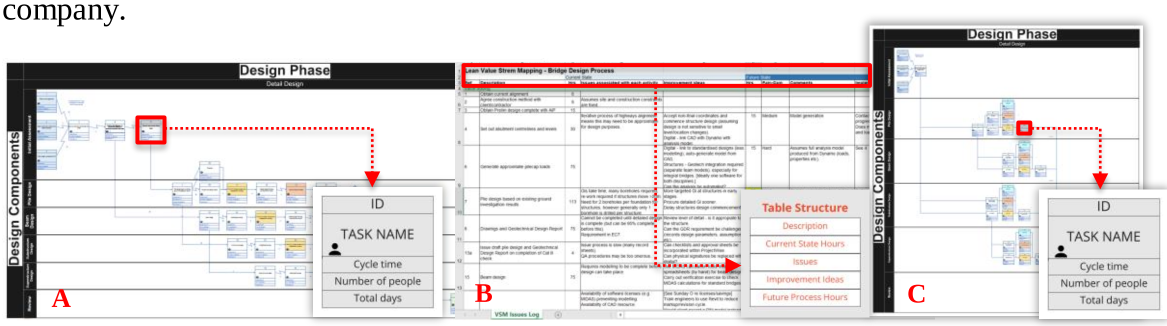

Figure 4. Current state process map for bridge design (5A), identification of issues and improvement opportunities table (5B) and perfect future state process map (5C).

JKK OF KEY DESIGN SUBPROCESSES

Process modelling was a part of the JKK implementation process in the Design Risk Management Process (DRMP). The main aim of the process modelling practice is to have the process work flow ready for the Designers and Principal Designer (PD) to support their understanding of the overall process and individuals' work activities. The practice required the involvement of the PD and designers with aid from the research team. This practice is believed to support the PD and specialist designers (i) to have a better comprehension of the DRMP, (ii) to acknowledge who is their 'foremost customers' within a process, and (iii) to obtain the knowledge of what is needed for the work deployment and whether the products meet the requirements. Figure 5 presents the final DRMP work flowchart and detailed analysis of the two features for each work unit. Although the practice sounds simple, applying it in a real-life context is difficult. The whole practice is a time-consuming task when trying to ensure the team members collaborate. It is difficult to represent the overall DRMP due to the different requirements and perceptions of the design team members.

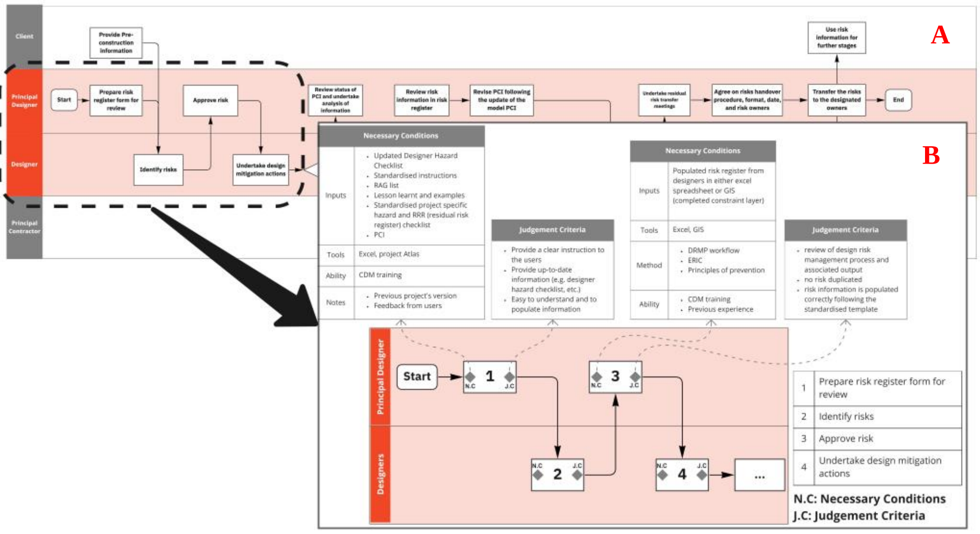

Figure 5. The Design Risk Management Process workflow chart (6A) and the necessary conditions and judgement criteria for each work unit (6B).

DISCUSSION

Table 1 summarises the key process modelling techniques discussed in this paper, when they should be adopted, their purposes, key elements, and the management effort required.

JKK has been recently introduced to the construction context and there are challenges associated with its implementation and adaptation to this new environment. The designers have faced difficulties in identifying tasks and their associated necessary conditions and judgement criteria due to a lack of clear client's requirements and pre-construction information, as also stated in Wynn and Clarkson (2018). There is also a lack of consideration of the JKK as a different approach to support commonly used design process modelling techniques. However, the introduction of JKK concept has partially aid the effort of understanding processes, sharing standard and knowhow between design team members. VSM, likewise, was not applicable in some cases, due to the issues concerning the element or component definition, as suggested by Rosenbaum et al. (2014), as well as the lack of clarity on how the design inventory should be calculated. There were also difficulties in collecting accurate data regarding the leading times and cycle times because of the uniqueness of the projects (Rosenbaum et al. 2014). This was found to be a time-consuming activity, as suggested by Forno et al. (2014), creating issues for continuous use of VSM.

All the different models, particularly the discipline-specific and BIM process modelling, were approached as a learning framework, providing opportunities for improvement and reflection for all the stakeholders involved in the process, corroborating with Tzortzopoulos and Sexton (2007). Other processes models functions were identified as enhancing communication and achieving consistency (Tzortzopoulos et al. 2005; Tzortzopoulos and Sexton 2007) through a common ground and shared understanding among the project participants. Process models can also provide a visual perspective of the full cycle (Martin and Osterling 2014) including different layers of information depending on the technique adopted and the role it performs, and can also formalise hidden processes as described in the clash management case study. Information can be displayed visually in rooms or virtual rooms, enhancing the participants' awareness about the activities, and this was achieved at the company through the adoption of visual management using digital collaborative platforms such as Miro or through the company intranet. A common ground is even more difficult to reach in a BIM-based design process due to the different standards and protocols that need to be followed; and process models seem to help in creating awareness of the steps, responsibilities, and stakeholders' and processes' interdependencies. This can be classified as a Lean contribution to BIM processes (Pedo et al. 2021), in which a Lean technique, i.e. process modelling, can be used to streamline and improve BIM processes.

Table 1. Guidance for process modelling in design.

Findings from the literature		Findings from the practical implementation in the case			
	Purpose and Maturity Level	***Company's Purposes***	***When***	***Key elements***	***Management of Process Models***
Generic swim-lane	**Purpose:** Describe the process (knowledge capture and analysis), and provide an overview of the entire process *(Aguilar-Savén 2004; Cooper and Kagioglou 1998; Tzortzopoulos et al. 2005)* **Level of process maturity:** Defined - documented processes standardised throughout the organisation *(Macintosh 1993)*	Achieve a comprehensive understanding of the design process, interconnection between multiple disciplines, and identify key interfaces	Overall process modelling of all design processes *e.g. 17 disciplines involved in the highways design*	Disciplines, design phases and overall activities.	Support high-level planning and provide a better understanding of interdependencies Standardise overall processes
Detailed swim-lane	**Purpose:** Describe the process (knowledge capture and analysis), and focus on information flow (Aguilar-Savén 2004; Sanvido 1990) **Level of process maturity:** Repeatable *(Macintosh 1993)*	Identify the key stakeholders and its interdependencies, roles and responsibilities, as well as opportunities for improvement, e.g. automation and standardisation opportunities	Discipline-specific processes *e.g. highways, drainage, structure*	Stakeholders (e.g. project manager, information manager, design team, other design disciplines), design phases, activities, decisions points, and key milestones	Top down approach to define the sequence of process to be modelled Support daily work and guide disciplines' schedule definitions (e.g. identifying new activities)
	Purpose: Describe the process (knowledge capture and analysis), and focus on information flow (Aguilar-Savén 2004; Sanvido 1990) **Level of process maturity:** Repeatable *(Macintosh 1993)*	Formalise hidden activities or steps, identifying resources, activity flows, and underlying purposes aligned with international standards	BIM and digital processes *e.g. clash management*	Stakeholders (specialists, e.g. design and BIM teams), activities and sub-activities, decision points, documents, database and connection with ISO or international standards	Top down approach to define the key processes to be mapped Support daily work, and standardise processes Tend to be adopted by specialists due to its high level of detail
Value Stream Mapping (VSM)	**Purpose:** Decision support to monitor and improve processes, and focus on information and materials flow *(Aguilar-Savén 2004; Rother and Shook 2003)* **Level of process maturity:** Managed - measured and controlled process *(Macintosh 1993)*	Create a roadmap for improvements between current and future states. Overall and systematic process improvement and waste elimination	Key design processes that represent large impact in the business *e.g. bridge design / structures*	Subprocesses of key design elements (e.g. beam design), activities, resource (number of people), cycle time, leading time, waiting time	Top down approach to define the processes to be value stream mapped Support a one-off improvement effort (removal of non-value adding activities) and schedule improvements (e.g. adjusting task durations) Future states considering different levels of planning (short-, medium- and long-term improvements)
Ji Koutei Kanketsu	**Purpose:** Decision support to monitor and improve processes, and support individuals in understanding the whole process *(Aguilar-Savén 2004; Manabe and Heller 2014)* **Level of process maturity:** Optimising - continuous process improvement *(Macintosh 1993)*	Improve and standardise individual tasks. Clearly state the input and output required for each activity.	Key process supporting the main design process *e.g. design risk management process*	Stakeholders, work flowchart, activities, necessary conditions, judgement criteria	Top down approach to define the processes to be mapped through JKK Support both the whole process and individual works

As argued by Tzortzopoulos and Sexton (2007), there is a need for meaningful participating and collaboration for a successful implementation, requiring appropriate involvement and engagement. The lack of engagement in designing and implementing the process models was identified as one of the key challenges associated with the stakeholders within the company. A joint effort is required to create process models, which can be currently enabled by virtual collaborative environments; also supporting new approaches for developing process models. The necessity of identifying a process owner and a workshop facilitator with process modelling knowledge was also observed as a significant aspect for process model development and implementation. However, a management effort is also needed for supporting process improvements considering the new digital environment. In addition to this, the management effort should consider different levels of planning (short-, medium- and long-term improvements), and define the management of steps for different needs in design.

CONCLUSIONS AND FURTHER RESEARCH

The complexity associated with the design process and sub-processes reflects in the different types of process models adopted within the company. The process modelling techniques adopted vary according to the different levels of detail required, different purposes and uses, different types of processes, and the elements needed. In addition to this, the management effort is also essential for supporting the design and implementation of process models. The investigation reviewed how process models were used in infrastructure engineering design, by analysing, developing, and implementing various process models' techniques for different purposes and by comparing them with the techniques investigated in the literature. The contribution of this investigation is related to an increased understanding of how process models should be used in civil engineering projects, as well as benefits, limitations, and challenges. This research is limited to the analysis of four process modelling techniques at a single design company, further work should explore a substantial number of process models' techniques and purposes, encouraging a further reflection about the benefits and barriers, as well as refining the recommendations.

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