Visual Management (VM) supporting collaborative practices in infrastructure engineering design

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Abstract. Managing the design of complex engineering systems requires an organisational structure and an information system to support collaboration among all stakeholders. Technological developments in information management have the potential to facilitate interactions across physical boundaries, even more during the Covid-19 pandemic. Visual Management (VM) is an information management strategy, as well as a means for communication between individuals, supporting collaborative work. However, there is a lack of effective understanding of how digital VM can support infrastructure engineering design. The adoption of digital collaborative VM in the context addressed is new, under rapid evolution, and there is limited understanding of how the users embrace VM while interacting with it. The aim of the paper is to explore the adoption of VM, focusing on digital whiteboards, to support collaborative practices in design processes. The ongoing investigation is carried out in collaboration with an infrastructure design and consultancy company, and follows the action research approach. The VM effectiveness was investigated by analysing the whiteboards applicability to diverse functions and comparing digital and manual implementations. Initial findings include understanding digital whiteboards as a means for collaboration among individuals with different perceptions to establish a common point of view, as it allows the information to be transferred across time and space, identifies abnormalities, and supports problem-solving. By creating a common ground, it has the potential to support complex and emergent interactions in the collaborative space.

1. Introduction

The growing complexity in collaborative design [1], combined with key innovations in the construction sector, have demanded major changes in traditional approaches. Managing stakeholders' interdependency is increasingly becoming challenging and complex, as many of its aspects need to be coordinated and integrated [2], even more during the Covid-19 outbreak, which required the shift of many work processes to an online and virtual format. In addition to that, the collaboration across social, professional, technological and cognitive boundaries and the integration of various streams of knowledge can be very challenging; however, it is often a requirement for the development of innovative solutions, especially for digital innovations [3]. Technological developments in information management have the potential to facilitate those interactions across organisational and physical boundaries. The lack of information and systems integration can affect the information transfer between

stakeholders and, consequently, managerial processes, potentially increasing project overruns and rework [4].

Visual Management (VM) can be defined as a set of practices that support communication through the adoption of different visual devices [5]. A visual device is a mechanism that influences, directs, limits or controls behaviour, making information essential to a specific task available immediately, without the need for explanation [6], making actions visible, and improving workflows [7]. VM is also described as a strategy for information management [8] and as means of communication between individuals with different perceptions who work collaboratively aiming a common point of view [9]. For instance, whiteboards have been found as a beneficial visual approach to communicating concepts and ideas, supporting discussions and collaboration between different stakeholders [10]. Existing literature shows that visual information can support the creation of a common ground [11]. Thus, it is important to understand the complex relationship between VM practices and cognitive processes of users, considering visual devices can facilitate the cognitive processes of understanding [12]. However, there is still a lack of research on how information is captured, represented, displayed and analysed by all users involved using shared visual representations [13]. Furthermore, the connections of VM and digital approaches although has been poorly investigated in the literature to date [8].

This paper reports findings of an ongoing Knowledge Transfer Partnership (KTP) project[1] with an infrastructure design and consultancy company. The aim of the paper is to explore the adoption of digital whiteboards to support collaborative practices in the design process, over an illustrating case study in highways and railways projects. This is done, firstly, by identifying and analysing the whiteboards applicability to various functions. Secondly, digital and manual whiteboards for Milestone and Phase Planning in the Last Planner® System (LPS) [14] implementation are compared. The comparison is to support the understanding of the digital whiteboard effectiveness, as well as the description of the phenomenon

2. Visual Management

VM is used for different purposes according to the context in which it is introduced. As described by Tezel et al. [5], some of the objectives are associated with increasing information availability and removing of blockages in the transfer of information. It is a strategy with potential to facilitate transparency across planning, execution and control interfaces and also information flow [15]. Other purposes for VM have been also pointed out in the literature, such as: enabling collaboration among stakeholders [16], encouraging a sense of shared ownership [5], which can also be related to commitment, engagement, integration, shared knowledge, as discussed by Brandalise et al. [17]. Understanding the key purposes, also named as functions in the literature, that VM can perform is instrumental for the dissemination of those devices into different sectors and work settings [5].

Valente et al. [12] proposed guidelines to support the adoption of VM, such as “encourage joint information processing”, considering visual devices can be used as catalysts for collaborative processes to facilitate a variety of tasks and achieve consensus. Furthermore, digital VM can be extremely dynamic, incorporating automation and several users’ perspectives [8]. However, managing the continuous flow of information among all stakeholders involved in the process is still a major challenge despite the recent technological improvements. Four scenarios for improving performance of VM with digital technology were suggested by Murata [18]: (i) view, expanding visual space, e.g. virtual, real and data world; (ii) time, considering the temporal extension, visualising not only the past and the future, but also in real time; (iii) solution, supporting not only the identification of the abnormality, but the entire problem solving process, such as root-cause analysis and devising countermeasures; (iv) place, visualising geographically different places.

Thus, according to Tezel and Aziz [8], the implementation of technology still presents some threats, e.g. neglecting the process and people and giving too much importance to the technology side, as well

[1] Knowledge Transfer Partnership (KTP) is a partially government-funded programme; and this KTP project aims to explore the integration of Lean and digital design, and it is sponsored by InnovateUK.

as deficient supply chain readiness to implement and operationalise the digital scenarios. Some barriers faced in the implementation of technology may be related to the lack of interoperability between technologies, lack of trained workforce, as well as lack of best practices and a business case [8].

3. Collaboration in design

Design is an activity in which a team should work collaboratively towards a final solution, which emerges as a result of the interaction between design team members, the artefact, other professionals and the environment [19]. Wood and Gray [20] describe collaboration as an interactive process which should engage autonomous stakeholders addressing the same problem. Collaborative work between different specialists and professionals, such as designers and contractors, is increasingly necessary in construction projects. In design, there is much interdependence between stakeholders, which puts pressure on the capability to communicate, transfer and share knowledge and information between them [21].

Research aiming to enable people to communicate, as well as share artefacts and information across distances has been done for many years [22], and there is a number of solutions supporting remote collaboration. However, the design of the digital systems rarely gives explicit attention to the coordination aspects, such as the cognitive aspect [23]. Most of software systems eventually fail without the cognitive work that people engage in with each other [24]. Technologies usually concentrate response coordination with a leader, implement a prescriptive process management approach, failing to consider the hidden cognitive work of coordination, and depend on devices that fail to completely support dynamic interactions [23]. Some difficulties were highlighted by Anumba et al [25], such as the use of diverse software tools and the lack of effective collaboration tools that are necessary to reduce the time and distance constraints, increasingly required by distributed design teams' work. Some ways of working, such as collaborative brainstorming on a whiteboard, cannot be completely supported in remote situations using traditional solutions [26]. Thus, the support for distributed creative working is described as limited by Gumienny et al. [22], with no support for the users who are actually collaborating with each other, resulting in an emotional disconnection.

In addition, collaborative processes demand a shared understanding by the stakeholders involved, rather than simply sharing knowledge [1], as it is a process related to the creation, exploration, information sharing, and integration of knowledge in order to develop common processes, products, and goals [27]. Shared understanding suggests an overlap of understanding among teams regarding a task [28], aiming to manage conflicts based on different perceptions. When people have a debate, there is a need of some common ground, which is defined by Kecskes and Zhang [29] as a dynamic construct that is jointly created during communication. The understanding of a dynamic environment within time and space, is also reated to situation awareness [30], and can be used for analysing, explaining, and improving collaborative working [31]. In fact, shared understanding, common ground and situational awareness emerged in the literature as relevant aspects to support collaboration.

4. Research Method

The overall methodological approach adopted in this investigation is action design research, as there is a strong involvement of the researcher and the company in the development of the solution, and there is no clear separation between developing and evaluating the artefact [32]. It is characterised by several learning cycles. The study was conducted in four stages: (i) diagnosing, related to the understanding of the overall problem, existing VM devices and collaboration routines; (ii) action planning and taking, associated with the proposition of new digital VM devices using collaborative digital whiteboards, such as Miro (www.miro.com) and Mural (www.mural.co); (iii) evaluation of the solution; and (iv) reflection upon the solution and critical analysis. The next cycles will further explore how users adopt and perceive digital collaborative VM by analysing the interface of collaboration and digital whiteboards, understanding its implementation in other sectors, and investigating a wide range of digital collaborative VM.

An empirical case study was carried out with an infrastructure design and consultancy company in the UK, as part of a KTP project. This research consists of a development and critical analysis of visual devices used by the company to support Lean implementations, such as LPS, focusing on digital whiteboards. The investigation is focused on highways and railways construction projects and have been chosen due to the fact that those projects had implemented Lean practices and digital VM to support design development. The researcher introduced the method in this context as well as engaged and trained people on how to use it. The main sources of evidence were: (i) participant observation of face-to-face and virtual collaborative planning sessions; (ii) small survey with workshop attendees; (iii) workshop with key stakeholders; (iv) development of training materials; and (v) training sessions.

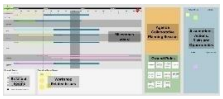
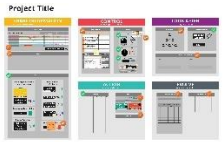
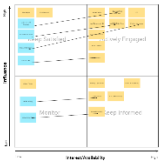
5. Description of whiteboards to support collaborative practices

The starting point was a practical problem identified in the company. It had decided to implement lean practices and digital solutions across the company to increase efficiency. VM and digitalisation have emerged as an opportunity to deal with the challenges related to the teams' fragmentation and lack of process transparency. In addition to it, digitalisation has become even more relevant due to the new coronavirus (Covid-19) pandemic, in which working from home has been accelerated, affecting ways of working, communicating, and collaborating. Most interactions among design teams started to be held in virtual environments.

The use of digital whiteboards has been found by company members as a beneficial approach to communicate ideas, concepts, actions, supporting virtual collaboration and integration, as well as discussion among different stakeholders based in different places. The digital whiteboards were described by the users as providing easily available information for remote collaboration, crossing the physical barriers. The experience was that everyone can contribute equally and support faster problem-solving. The implementation of the whiteboards was done across different design projects, teams, and organisational levels as well as for different functions, as described below (**Table 1**). Nine different uses and functions were identified, however, the adoption of the whiteboard for the LPS implementation was analysed in detail (**Table 1**, ID 1), comparing manual and digital practices. The adoption of digital platform for the LPS emerged as an opportunity to assist remote planning and coordination of activities throughout the restrictions of working from home, and the other uses emerged as a consequence of its initial use, without a problem identification in advance. The teams became familiar with the whiteboard interface and its functionalities, facilitating the whiteboard dissemination for other uses.

Digital whiteboard (**Table 1**, ID 1) was adopted to support the collaborative planning sessions, which are undertaken along the whole design process to develop a high-level schedule, reviewed every three or four months. Those sessions are also called master and phase scheduling in the LPS, specifying what 'should' be done when and by whom. These elements are part of the LPS planning and control process, which can be described in five stages: (i) master scheduling, (ii) phase scheduling, (iii) lookahead planning, (iv) commitment planning, and (v) learning; and those are based on 'Should-Can-Will-Did' definitions [14]. The collaborative planning sessions were focused on the agreement of deliverable dates already defined in the long-term plan and the purpose is to ensure that all parties understand the timeframes, their responsibilities, and consequently, the impact of not delivering their tasks. So, risks and assumptions were identified, understood, and logged during the session for continuous review and management. A practitioner with knowledge in Lean, who is external to the project, usually chairs the meeting, aiming to bring a neutral perspective to decision making points and keeping the meeting in focus.

Table 1. Functions of digital whiteboards.

ID	Name	Description	Illustration
1	Digital whiteboard for implementing LPS	Digital whiteboard (MURAL) for agreeing of the next steps and long-term plan, as well as identifying and managing key risks, actions, assumptions and opportunities.	
2	Digital whiteboard for process mapping	Digital whiteboard (Miro) for design process mapping and value stream analysis, supporting the identification of the current state process and opportunities to improve.	
3	Digital whiteboard for designing new systems	Digital whiteboard (Miro) for devising new systems, e.g. VM dashboard mock-up and lessons learnt system development, through collaborative discussions and agreements.	
4	Digital whiteboard for devising new strategies	Digital whiteboard (Miro) for developing new Lean strategy and business model, describing how Lean is implemented across the different project stages at the company, as well as collating the different initiatives into one document that will guide future implementations and training.	
5	Digital whiteboard for brainstorming	Digital whiteboard (Miro) for brainstorming and collaborative problem identification. It was mainly adopted as a support for the KTP project development, focusing on the identification of key Lean-BIM improvement opportunities.	
6	Digital whiteboard for meeting structure	Digital whiteboard (Miro) for meeting structure, including strategic alignment, agenda, workplace and minutes, actions and responsibilities. It was used to support different types of meetings, e.g. KTP meetings, drainage strategic meetings, LPS meetings.	
7	Digital whiteboard for identifying constraints and requirements from design disciplines	Digital whiteboard (MURAL) for constraints identification can be used to recognise the information each discipline requires. It was suggested to a project in which the constraints were poorly identified.	
8	Digital whiteboard for mapping stakeholders	Digital whiteboard (MURAL) for mapping key stakeholders supported their identification and classification according to the interest/availability and influence in the company.	
9	Digital whiteboard for joint research [a]	Digital whiteboard (Miro) for joint research development was adopted to support researchers in brainstorming, insights recordings, papers discussion and making notes, and artefacts development.	

[a] This purpose was identified by the researcher from outside of the company and the KTP project

5.1. Pre-pandemic manual VM for implementing LPS

Prior to the restrictions imposed due to the pandemic, those discussions were held through face-to-face meetings. The teams adopted two different collaborative visual boards to support the discussions and agreements (**Figure 1**). The board with milestones and deliverables (**Figure 1A and 1B**) was the main

VM device used during the meeting, although there was also a board supporting the discussions related to assumptions, key actions, risks, and opportunities (**Figure 1C**) emerging during the meeting. These were flexible and simple, encouraging greater engagement and ownership of the work by participants. The routines related to the use of the device are described in **Figure 2**.

Figure 1. Manual board for collaborative planning. Figure 1A represents the moment in which each discipline plans individually; Figure 1B, the collaborative planning; and Figure 1C, the board with assumptions, risks, actions and opportunities.

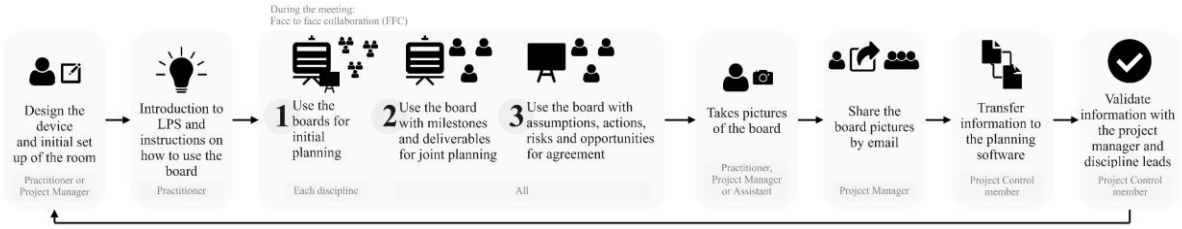


Figure 2. Manual VM practice.

The project manager or practitioner used to support the set-up of the room and visual board display, including the general milestones on the board prior to the meeting, which were based on the master schedule milestones. A brief introduction to the LPS concepts with key instructions on how to use the board was provided at the beginning of the meeting. To begin with, each discipline used the board for initial planning (**Figure 1A**), developing a high-level programme to fit with client and procurement requirements. After that, all disciplines members used the board simultaneously (**Figure 1B**) for collaborative planning. Each discipline outlined their programme to the group and collectively they reviewed, challenged and improved the plan, also identifying issues or constraints, and developing actions or mitigations. After the meeting, the information was recorded through pictures of the board, that were shared with the design and project control team. Then, the information was updated into the master schedule, also feeding and guiding the other levels of planning. This was classified by the team as a waste in the process due to the rework required and time spent to transfer the information from the manual sticky notes to the planning software. The notes used to be very simple and handwritten, demanding time to understand its connection with the activities in the planning software. Taking this into consideration, it was necessary to confirm and validate the new programme with the discipline leads before publishing a new version. The main issues with the manual VM devices were related to the difficulty in maintaining the information up to date, recording and sharing the information properly and decision-making with the geographically distributed teams. There was also a lack of space to display the VM devices in the company offices, as the meeting rooms were shared between different projects, limiting the availability of those devices during the meeting.

5.2. Digital VM for implementing LPS

Since early 2020 those meetings started to be held in virtual environments using MURAL and Microsoft Teams to support it. The latter one provided means for communicating and distributing information through synchronous distributed collaboration. The digital whiteboard in MURAL (**Figure 3**) was adopted for agreeing on the next steps and long-term plan, as well as identifying and managing key risks, actions, assumptions and opportunities. It also included the agenda, and a section with key ground

rules in the digital environment. The board was updated every 3 or 4 months, depending on the project requirements, and it was used in a weekly basis to support short-term discussions.

The visual and non-visual work related to the digital whiteboard is described in **Figure 4**. Similar to the manual practice, the Practitioner or Project Manager supported the design of the device and the initial set up. The Project Manager and the Practitioner would have a catch-up to define the agenda and aim of the meeting. Thus, the collaborative board link and agenda were shared with the team prior to the meeting, requiring the discipline teams to populate and familiarise themselves with the board before the session. Following the same steps as the face-to-face meeting, a training was carried out. The instructions were usually given only in the first collaborative planning session of a project, assuming the teams would know how to use the board in the following ones.

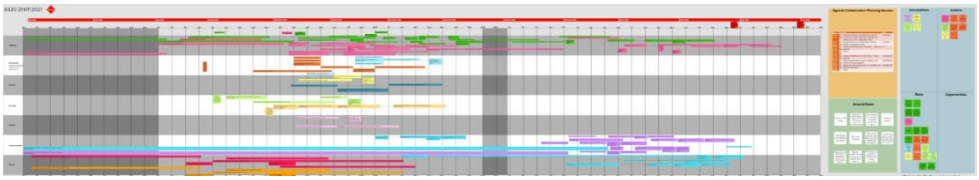


Figure 3. Digital whiteboard for master and phase planning.

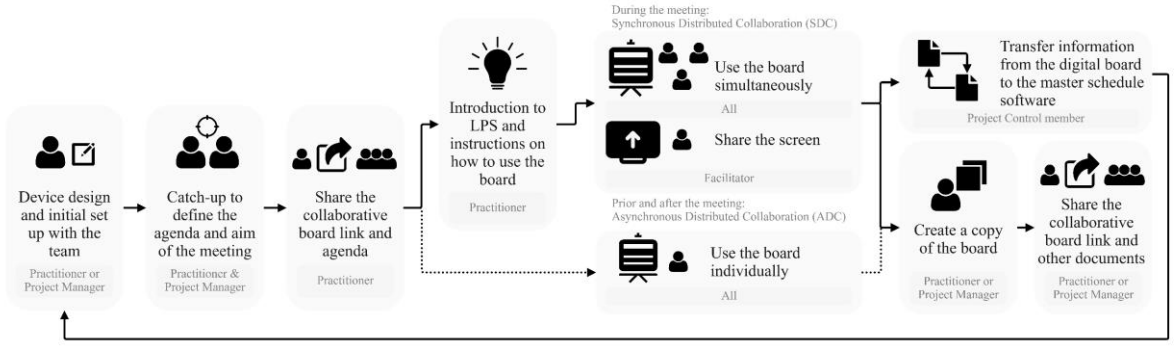


Figure 4. Digital VM practice.

During the meeting, some team members adopted the board simultaneously with access through a link, whereas the facilitator shared the screen with the board to enable the visualisation for those participants not comfortable in using the whiteboard by themselves. The platform still presents a functionality to bring all the participants to the same view, enabling everyone to visualise the same information at the same time and have directed focus, regardless the approach adopted. The meeting was carried out through synchronous distributed collaboration, allowing interactions among all stakeholders simultaneously. However, the use of the digital whiteboard prior and after the meeting through asynchronous distributed collaboration was also facilitated, allowing the design team members to use the board individually with an easy access through the same link shared previously. Following the meeting, the Project Manager would share the board link and other documents with the team and with the project control team, so they were able transfer the information from the digital board to the master schedule software. A backup of the board was also created with the aim of tracking the decisions made during the sessions. The connection between the whiteboard and the master schedule software was still not automated, requiring someone to input the information into the Primavera P6 software. However, the process was facilitated due to the fact the information was already digital and the activity reference numbers were included, making it easier to match with the activities in the software.

Some of the positive aspects highlighted by the project team were related to the visualisation of the programme, collaboration among all parties, raising issues and presenting a simplified programme, as well as the time efficiency related to having the plan already available to the team without a need to digitalise it. The key challenges identified were described as: discussions were held among a few

individuals and not everyone was as involved in the same level of collaboration, and IT issues relating to access to the board and breakout rooms were also classified as challenges.

6. Discussion

The use of digital platforms started with the assumption that the problem to be solved was identified, i.e. changing from a face-to-face to an asynchronous distributed collaboration to support remote work, and the digital whiteboards were identified as a suitable solution for that gap due to its easy information access and collaboration aspect. It followed the formal problem-solving practice, as defined by von Hippel and von Krogh [33]. Thus, the digital whiteboards started to be developed and used in the company as an approach to recreate the collaborative environment as it existed in the face-to-face planning sessions. However, the solution started to solve problems not previously identified, following the informal problem-solving approach proposed by von Hippel and von Krogh [33]. This approach suggests that a need and a solution can be discovered simultaneously, a need–solution pair being thus tested for viability. So, the identification of different functions for the digital whiteboard emerged during its use due to the platform flexibility, in which the information and the interface can be changed in response to the dynamic environment, suggesting that new problems could also be solved without a previous problem formulation. Thus, the flexibility to adapt the devices according to the users' needs over time and requirements was considered a positive characteristic of the digital whiteboards. As suggested in the literature, this could reduce costs and time associated with the problem identification [33].

New technologies can also support new ways of communication, collaboration, and visualisation, by creating a common ground that is continuously created [29] and recreated. Thus, digital whiteboards also present the potential to facilitate the transfer of information, to speed up communication and decision-making, as suggested by Koskela et al. [34], supporting complex and emergent interactions in the collaborative space. The creation and use of information were based on a more dynamic environment, allowing everyone to interact simultaneously even through asynchronous collaboration through easy access and use of the platform. Furthermore, its usefulness in the digital context was a response to Covid-19. According to the company project director, 'the use of MURAL allowed everyone to input simultaneously without being overwhelming'. Digital whiteboards allow the information to be transferred across time and space, as argued by Murata [18], supporting the understanding of the dynamic environment through better situational awareness [30]. Virtual meetings using digital whiteboards allow people from different offices to meet without the time and expense of travel, also allowing a greater number of stakeholders to attend. It was considered by a team member as a 'useful structure to pull all teams together and understand the key milestones and risks to the programme', allowing the engagement and commitment of different stakeholders in identifying not only any abnormality in the schedule, but also the entire problem solving, such as the causes and countermeasures, in the same interface, corroborating with the 'solution' dimension suggested by Murata [18].

However, sharing knowledge is not enough to support collaborative practices. A shared understanding is also required to support the development of products [27]. So, digital platforms supported the joint learning through combining different perspectives and interests [27], promoting the development of the design projects as well as the development of new VM practices for different purposes. In addition to that, digital environments are changing the effort needed to set up meetings. Less set up effort is required, considering the sessions do not need to be scheduled in advance compared with the face-to-face approach, and rooms do not need to be booked. Also, the size of a room is not a concern anymore, as digital rooms can fit a large number of participants. However, the excess of virtual meetings and increased people accessibility can be considered a challenge, as people may develop meeting tiredness and collaboration can also become a challenge. Thus, people may be collaborating differently over digital and manual devices and the dynamics may be different; so the devices should consider those different aspects.

The required learning curve was short, even though a minimal level of training was needed, as the whiteboard for collaborative planning sessions were easy to use and mirrored the manual board,

traditionally adopted by the company. However, there were still some challenges associated with the adoption of different platforms simultaneously [25], e.g. the digital whiteboard and Microsoft Teams, in which more digital skills were required. This can also be related to the readiness needed to implement and operationalise digital VM, as well as the lack of interoperability between technologies, as argued by Tezel and Aziz [8]. The level of finishedness required was higher than the level in the manual board, considering it was possible to input more information on the sticky note, consequently, inhibiting modifications and requiring more time to insert the information. The social aspect can also become a barrier, as it can be more difficult to build relationships when interacting virtually since early stages of a project, and people can feel neglected [8], so that face-to-face interactions can be recommended at the start of a project to tackle those challenges. In addition to this, emotional challenges in digital environments could be related to the lack of ownership, which may be associate with the lack of identification with the digital technologies.

7. Conclusions and Further Research

Digital VM can be adopted as a means for collaboration among individuals with different perceptions to establish a common point of view. These aspects were explored in this paper through the analysis of VM supporting collaborative practices in infrastructure engineering design processes. Different functions of digital whiteboards were investigated, focusing on whiteboards for implementing LPS. The investigation helped to better understand the effectiveness of collaborative VM in digital infrastructure engineering design, by analysing its applicability to diverse functions and comparing digital and manual implementations. It considered the human-technology interaction through different types of collaboration, e.g., asynchronous and synchronous distributed collaboration, and the users' perception in collaborative practices to support common ground, shared understanding and situational awareness. Collaborative digital VM allows the information to be transferred across time and space, identifying not only the abnormality but also supporting the problem solving. By creating a common ground, the transfer of information, communication and decision-making can be improved, and the new technologies can support complex and emergent interactions through new ways of communication, collaboration, and visualisation. This research is limited to the analysis of digital whiteboards, further work should explore a substantial number of other digital collaborative VM devices, encouraging a further reflection about the benefits and barriers, as well as users' perceptions. Further investigation is also required in the interface of collaboration and digital VM, considering different the collaborative mechanisms, knowledge to be integrated and factors that influence in creating a common ground.

References

[1] Kleinsmann M and Valkenburg R 2008 Barriers and enablers for creating shared understanding in co-design projects *Des. Stud.* **29** 369–86
[2] Hooper M and Ekholm A 2010 A pilot study: Towards BIM integration - An analysis of design information exchange & coordination *CIB W78 27th Int. Conf.* 16–8
[3] Pershina R, Soppe B and Thune T M 2019 Bridging analog and digital expertise: Cross-domain collaboration and boundary-spanning tools in the creation of digital innovation *Res. Policy* **48** 103819
[4] Eastman C, Teicholz P, Sacks R and Liston K 2008 *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*
[5] Tezel A, Koskela L and Tzortzopoulos P 2016 Visual management in production management: A literature synthesis *J. Manuf. Technol. Manag.* **27** 766–99
[6] Galsworth G D 2017 *Visual Workplace Visual Thinking : Creating Enterprise Excellence Through the Technologies of the Visual Workplace, Second Edition*
[7] Beynon-Davies P and Lederman R 2017 Making sense of visual management through affordance theory *Prod. Plan. Control* **28** 142–57
[8] Tezel A and Aziz Z 2017 From conventional to it based visual management: A conceptual discussion for lean construction *J. Inf. Technol. Constr.* **22** 220–46

[9] Lindlöf L 2014 *Visual Management – on Communication in Product Development Organizations* (Chalmers University of Technology)
[10] Shae Z Y, Tseng B and Leung W H 2001 Immersive Whiteboard Collaborative System *Ann. Softw. Eng.* **12** 193–212
[11] Gergle D, Kraut R E and Fussell S R 2013 Using visual information for grounding and awareness in collaborative tasks *Human-Computer Interact.* **28** 1–39
[12] Valente C P, Brandalise F M P and Formoso C T 2019 Model for Devising Visual Management Systems on Construction Sites *J. Constr. Eng. Manag.* **145** 04018138
[13] Yusoff N M and Salim S S 2015 A systematic review of shared visualisation to achieve common ground *J. Vis. Lang. Comput.* **28** 83–99
[14] Ballard G and Howell G 1998 Shielding Production: Essential Step in Production Control *J. Constr. Eng. Manag.* **124** 11–7
[15] Brady D A, Tzortzopoulos P, Rooke J, Formoso C T and Tezel A 2018 Improving transparency in construction management: a visual planning and control model *Eng. Constr. Archit. Manag.* ECAM-07-2017-0122
[16] Ewenstein B and Whyte J 2009 Knowledge Practices in Design: The Role of Visual Representations as `Epistemic Objects' *Organ. Stud.* **30** 07–30
[17] Brandalise F M P, Pedo B, Viana D D and Formoso and C T 2021 Exploring Visual Management Purposes in Construction Projects *Proc. 29th Annu. Conf. Int. Gr. Lean Constr.* 289–98
[18] Murata K 2019 On the role of visual management in the era of digital innovation *Procedia Manuf.* **39** 117–22
[19] Saad M and Maher M Lou 1996 Shared understanding in computer-supported collaborative design *CAD Comput. Aided Des.* **28** 183–92
[20] Wood D J and Gray B 1991 Theory of Collaboration
[21] Emmitt S, Sander D and Chritoffersen A K 2006 Implementing of ValueThrough Lean Design management
[22] Gumienny R, Meinel C, Gericke L, Quasthoff M, LoBue P and Willems C 2011 Tele-Board: Enabling Efficient Collaboration In Digital Design Spaces Across Time and Distance *Design Thinking* vol 15 (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 147–64
[23] Maguire L M D 2019 Managing the hidden costs of coordination 71–93
[24] Woods D D and Allspaw J 2019 Revealing the Critical Role of Human Performance in Software 1–13
[25] Anumba C J, Ugwu O O, Newnham L and Thorpe A 2002 Collaborative design of structures using intelligent agents *Autom. Constr.* **11** 89–103
[26] Gumienny R, Gericke L, Wenzel M and Meinel C 2013 Supporting creative collaboration in globally distributed companies *Proc. ACM Conf. Comput. Support. Coop. Work. CSCW* 995–1006
[27] Pikas E, Koskela L, Treldal N, Ballard G and Liias R 2016 Collaboration in design - Justification, characteristics and related concepts *IGLC 2016 - 24th Annu. Conf. Int. Gr. Lean Constr.* 143–52
[28] Maher M Lou, Cicognani A and Simoff S 1997 An experimental study of computer mediated collaborative design *Int. J. Des. Comput.* **1** 1–5
[29] Kecskes I and Zhang F 2009 Activating, seeking, and creating common ground *Pragmat. Cogn.* **17** 331–55
[30] Endsley M R 1995 Toward a theory of situation awareness in dynamic systems *Hum. Factors J. Hum. Factors Ergon. Soc.* **37** 32–64
[31] Koskela L, Pikas E, Gomes D, Biotto C, Talebi S, Rahim N and Tzortzopoulos P 2016 Towards shared understanding on common ground, boundary objects and other related concepts *IGLC 2016 - 24th Annu. Conf. Int. Gr. Lean Constr.* 63–72
[32] Sein M K, Henfridsson O, Purao S, Rossi M and Lindgren R 2011 Action design research *MIS Q. Manag. Inf. Syst.* **35** 37–56

[33] von Hippel E and von Krogh G 2016 Problem solving without problem formulation *Organ. Sci.* **27** 207–21
[34] Koskela L, Tezel A and Tzortzopoulos P 2018 Why Visual Management? *26th Annu. Conf. Int. Gr. Lean Constr.* 250–60

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