EXPLORING VISUAL ASSET MANAGEMENT COLLABORATION: LEARNING FROM THE OIL AND GAS SECTOR

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Visual Asset Management (VAM) is defined as a visual, collaborative and cloud-based database application for project sharing, viewing, delivery, operation and maintenance. VAM provides a platform that contains multiple visual data sources of an infrastructure project, including Building Information Models, associated asset documentation and 360° photographic images of the asset. This research presents three cases of the use of VAM in major oil and gas platforms in the North Sea, identifying the challenges resolved using VAM, the benefits realised as well as the opportunities for learning and transfer of VAM to the construction industry. The findings demonstrate that VAM can be used effectively to support decision making process during infrastructure project planning and development. The case studies further demonstrated that VAM will be particularly beneficial in facilities management and built asset operation, thereby, ensuring the accuracy and reliability of information for operations and maintenance. Due to the increasingly complex nature of projects in terms of size, information technology and security, realizing these benefits would require a learning process for all stakeholders involved in procuring and managing assets. This research proposes stepped change and learning opportunity for built assets value maximization and delivery, management and operation efficiency using VAM.

Keywords: collaboration, BIM, Visual Asset Management

INTRODUCTION

Efficient collaboration and productivity within the construction and energy sectors has always been crucial to business profitability and sustainability, with both sectors shifting their focus in relation to projects delivery, away from the chain of production activities towards developing and applying efficient collaboration and innovation in the creation, sharing and collection of relevant information among interdisciplinary professionals (Eastman *et al.,* 2011, East 2016, Oil and Gas Authority 2017, Leon *et al.,* 2015). The reason for this shift of paradigm is located in productivity difficulties and operational inefficiencies, compounded by the increased complexity of the project requirements. The result of these challenges are large cost overruns, project delays, rework in addition to

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operational bottlenecks when the asset is in use (Bordat *et al.,* 2004, Love *et al.,* 2016, Ahiaga-Dagbui *et al.,* 2017). To tackle these issues, both industries are focusing on adopting innovative digital technologies, including Building Information Modelling (BIM) and other visualisation tools, to aid the planning and delivery of projects in an attempt to tackle some of the difficulties identified above. At the core of these technologies are the concepts of collaboration, visualisation and cost efficiency. The specific research builds upon Lobo and Whyte (2017), Hobday *et al.,* (2005), Ewenstein and Whyte (2007), Leon *et al.,* (2015) and Bucciarelli (1994) who noted that the development of innovative, digitised and disruptive technologies for multi-firm collaborations will be very crucial for tackling issues of efficiency and maximised value-creation. Tackling the potential uncertainty in multi-firm projects carries risks that most companies are unwilling to take (Hobday *et al.,* 2005), which in turn challenges effective collaboration. However, disruptive technologies present a real alternative to the way we approach these challenges, such as communication and management applications within Internet of Things (IoT) and cloud technologies. Embracing disruption and introducing alternative digitised services for managing assets can reduce operational disruptions and provide new opportunities to address poor productivity and projects inefficiency.

Collaboration, productivity and cost control have been developing as a central theme both for oil and gas and construction, highlighting the importance of shared decision making, informed projects evolution and data openness and sharing for successful projects completion (Marquardt and Nagl 2004, Oil and Gas Authority 2017, Eastman *et al*., 2011, Leon *et al.,* 2015). This research acknowledges that collaboration between different teams with varying expertise can be greatly enhanced by the use of visualisation tools and techniques. Visual representations and their impact on problem finding and design solutions development has been examined in great detail in previous research. Schön's (1991) seminal work claimed that visual material can substantially support cognitive abilities while Lawson (2005) noted that design thinking is promoted with the application of visual representations and stimuli depicting varying levels of details and design scales. Research by Ewenstein and Whyte (2007) explored visual representations as 'knowledge artefacts' applicable for communication and ideas development. These visual means of communication are important for a wide spectrum of sectors, from engineering (Pahl and Beitz, 1995; Bucciarelli, 1994) to design (Schön, 1991).

Both oil and gas and construction industries struggle with collaboration, productivity issues and cost control and have sought after technologies and processes that might be able to help them circumvent the problem. As a result, they have adopted visual collaborative platforms, like VAM and BIM accordingly. BIM, in addition to other disruptive technologies, have been introduced in the construction industry to help with collaboration and collect operation data during construction. On the other hand, oil and gas industry is beginning to apply VAM, which is a digitised collaborative project delivery and asset management platform for minimal disruptions when maintaining or inspecting assets by allowing an aggregated view of a project, its elements and its lifecycle. In this paper, we introduce VAM as a complement of BIM processes that are already transforming the way construction projects are delivered and operated. VAM accommodates collaboration, shared visualisations and understanding for asset management to achieve a high degree of synchronised actions and information flow, and to further support efficient collaboration among partnering companies. The research is also focusing on assets management, which is becoming a central theme of projects organisation and planning since it is a vital parameter for ensuring project delivery within the required time, cost and quality.

Based on the theoretical discourse described above, this research presents a VAM framework with the implementation of a hybrid collaborative platform that provides a visual front end asset management and incorporates accurate 3D representations and data. The technology provides a facility that enables the supply chain to collaborate, and improves data capture, information management and project coordination and planning. The rest of the paper is structured as follows: a review of collaborative practice enhancement using visual stimuli is presented, together with an overview of VAM and some common challenges between oil and gas and construction. Afterwards, three different case studies are presented where VAM was applied, thus demonstrating transferable capabilities and applications across the two industries, energy and construction. The paper concludes with recommendations for further research and development on VAM systems.

Theoretical Framework: Collaborative Practices Enhancement by Visual Stimuli and VAM

Impact of Visualisations on Collaboration

Why visualisations are so important? Visualisations contain the potential for ideation, reflection and projects' development, hence, teamwork and interdisciplinary collaborations can be strongly supported with the implementation of visual representations (Ewenstein and Whyte 2007, Leon *et al*., 2015). By taking into consideration the fact that design solutions will develop in an adaptive and iterative manner (Schön 1991), collaborative teamwork can only enhance this process through the acquired knowledge and team members' contributions. When it comes to the energy and construction sectors especially, design problems are ill-defined by their nature and they are considered moving targets that quite frequently 'do not have a solution but only a resolution' (Arias 1995), hence, multidisciplinary teamwork can support successful changes, conflicts and adaptations. Having the support of visual representations further enhances these collaborations (Leon, *et al.,* 2014a). Most importantly, this research is showcasing how digital and virtual sharing of information and visualisations can be a facilitator for collaborative design and assets management, by assisting interdisciplinary professionals externalising and communicating their ideas, hence leading to cost and time savings in major projects.

Visual Asset Management

VAM is a digital platform that supports 'visual management' i.e. visualisation tools for information sharing, asset operation, security management and improving understanding of customer needs and organisational principles (Tjell and Bosch-Sijtsema, 2015; Eppler and Burkhard, 2007). 'Visual' refers to representations that transfer information within any type of design projects for digitally enabled coordination and delivery (Whyte and Lobo, 2010; Lobo and Whyte, 2017) as well as 4D Building Information Modelling (BIM) that connects temporal and spatial aspects of a project. This integration is thus supporting viewing, scheduling and communicating of a project (Eppler and Burkhard, 2007; Eastman, *et al.,* 2011), whereas, project digital delivery, similarly to Integrated Project Delivery (IPD), is defined as integrated software both within and across firms, supported by extranets, management and computer aided design types of software (D'Adderio, 2001, Poirier, *et al*., 2016). 'Asset Management' refers to aligning operational and business strategies for reliable assets function, optimum performance and overall site productivity, characteristics that are shared between construction and oil and gas (Tezel, *et al*., 2009, Fuggini *et al*., 2016).

Complex problems solution-finding can be supported with the application of collaborative practices, as described by Fischer (2000), who argued that the creation of shared understanding among stakeholders can lead to ideation and development of innovation. These processes can further flourish with the application of Computer Supported Cooperative Work (CSCW), which provide appropriate project information through digital mechanisms and avoid cognitive overload (Bucciarelli 1994). These types of system can embrace interactions with users and visual data, thus enabling data exchange and exploration and allowing space for production, coordination and communication (Tezel, *et al*., 2009; Leon *et al*., 2014a). From this base, the VAM studied in this research has expanded to build upon CSCW technologies, assisting in the analysis and evaluation of virtual prototypes in a realistic manner and quite often more effectively than physical or visual models. This research is moving forward from examining visual, pictorial, geometric and scripted elements of assets portfolios to considering the dimension of project planning and most importantly, the multi-firm and multidisciplinary perspective of contemporary projects creation and development with a global view of assets and their specifics. Access to this information would enable minimising disruptions, for reasons like maintenance or inspections, and it would maximise assets usability and efficiency. Linking different ideas on visual data, multi-firm and interdisciplinary collaborations and project planning casts light on VAM as an intrusive technology framework for project planning and asset management, thus, enabling added value and strategic collaborative decisions by allowing an aggregated view of a project, its elements and its lifecycle.

Industry challenges and applications

Application of the aforementioned technologies within infrastructure projects would be useful in maintaining a fit-for-service condition of an asset, thus ensuring safety, efficiency and reliability for operations and clients cost effectiveness. This can have considerable cost saving implications particularly from a facilities or asset management perspective. In the case the O&G, cost efficiency and productivity optimisation has mainly be achieved through applying design, engineering and operational integration (Marquardt and Nagl, 2004). The industry is characterised by quasi-static processes that the subject of slowly varying constraints (Fuggini *et al*., 2016). However, the recent lower-for-longer oil price environment within O&G industry demanded for enhanced efficiency within the industry, similarly to the crises within infrastructure projects (Eastman *et al*., 2011). As a result, professionals in both industries are required to move from a deterministic approach to a probabilistic approach with uncertainty and variability reduction, more precise estimations of failure points and adoption of condition based monitoring, thus optimising asset management (Neumann and Krieger, 2012). *Therefore, building project lifecycle intelligence of a built asset within a digitised framework would not only allow more accurate cost predictions but it would also promote health and safety within operations.*

VAM framework: From Oil and Gas to Construction Industry

This research studied the application of a specific VAM platform in the Oil and Gas (O&G) industry, namely R2S Mosaic® by Return to Scene (R2S). R2S Mosaic (VAM R2S) is used predominantly by international energy companies as a VAM to record, operate and manage complex assets, particularly in offshore locations. VAM R2S enhances planning, collaboration and presentation by consolidating, contextualising and presenting multiple forms of information in a user-friendly, visual form (Figure1). The VAM framework involves the capture of 360-degree high definition photographs of remote assets that are developed in Plant Design Management System (PDMS) files and combines these with a software interface to create virtual, interactive walk-throughs. Associated data can then be added and accessed from within these images, providing a highly intuitive method of recording, editing, sharing and presenting information. Such an inclusive and visual platform not only encompasses multiple types of information, but also allows both synchronous and asynchronous, face-to-face and distant collaboration, communication and planning Figure 2), thus augmenting understanding for assets management. When linked to other client systems, databases and live data feeds, R2S becomes a knowledge portal, through which multiple participants, departments and disciplines can collaborate and learn. Even though some of these systems are relatively well developed in industries such as O&G, there has not been the uptake of these technologies in the construction industry. Thus, the challenges of poor coordination, information exchange, collaborative and front-end planning are still pervasive in the industry (Ozorhon and Cinar 2015, Adam *et al*., 2017).

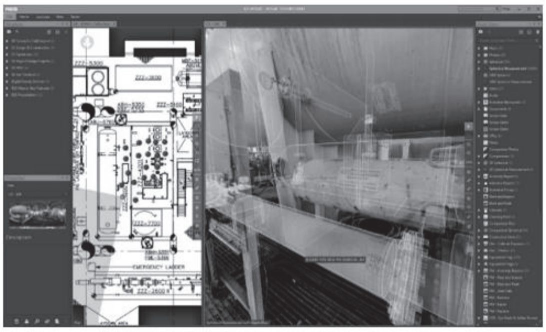

Figure 1: VAM R2S graphical user with 360-degree photographs & databases interface

Figure 2: Asynchronous and distant collaboration using VAM in R2S

RESEARCH APPROACH

This research adopts a case study approach by appraising three examples of the application of VAM in the O&G industry so as to present learning opportunities for cross-industry knowledge transfer to construction and infrastructure projects. Case studies are appropriate where an in-depth knowledge of an individual example is more helpful than fleeting and superficial knowledge about a larger number of examples (Gerring 2006). The purpose of the study, at least in part, is to shed more light on the larger population by critically examining the phenomenon in one, or a few. It is preferred research strategy when the phenomenon and its context are not readily distinguishable and when a deeper understanding of practical issues on how things actually work is required (Denzin and Lincoln, 2011). Within this research, case studies provide the insight regarding VAM applicability within real-life context while they share some important characteristics (precision, quantification, objectivity and rigor). The first two projects cover the planning and actual delivery of projects whiles the third case study is chosen to demonstrate the utility of VAM for project team collaboration in a data hub and the shared approach was related to drawing out themes or findings which might be more readily transferred to construction.

VAM CASE STUDIES

Case study 1: Chevron's Erskine offshore Oil and Gas platform - Reinstatement
The first case study focussed on the application of R2S VAM for efficient asset reinstatement of an offshore O&G platform in the North Sea (Christie, *et al.,* 2015). A fire on Chevron's Erskine offshore O&G platform in the North Sea in early 2010 resulted in operational shutdown, and a fire on a Normally Unmanned Installation (NUI) led to an

eight month restoration effort. Having been made aware of the benefits of VAM technology by a tier-one service provider, the Offshore Installation Manager (OIM) for the asset proposed the application of R2S. In using VAM, the OIM noted:

> …we faced pressure around bed space, so the visualization capture allowed us to plan, capture, build, deliver and manage a solution to this challenge. It also meant that we could limit the number of offshore surveys required in the project because we effectively had a pair of eyes on the installation at all times thus reducing the numbers required on board.

This VAM system proved valuable for Chevron during the reinstatement process that the impact to the business was realised beyond the scope of the original project. Chevron has since completed the roll out of the spherical Photographic VAM system across its North Sea assets identifying it as a step change in providing benefits relating to maintenance, reliability and integrity management including improvement in planning work for turnaround coordinators (Christie, *et al*., 2015). It also allowed for staff or visitors to explore work areas prior to mobilization for campaign maintenance, strengthening defect identification and work pack pre-population for reliability.

Case Study 2: Magnus Life Extension and Eastern Trough Area Project- Life Extension Project Planning

The second case study examined the application of R2S VAM for planning purposes. British Petroleum (BP) applied R2S in 2016, within the North Sea for the Magnus Life Extension Project (MLXP) and Eastern Trough Area Project (ETAP) Life Extension Project (ELXP). A saving of 75 man years in time was made - equating to almost $20 million saved on items including office space, flights, beds and other associated travel and accommodation costs. As Little *et al.,* (2016) explained, the North Sea Renewal Campaign commenced in early 2014 and incorporated two assets which form the focus of this case study. The renewal campaign was undertaken to tackle integrity and reliability issues to improve operating efficiency and avoid larger interventions (Maslin, 2013). These non-shutdown life extension projects sought methods of maintaining production while considerably increasing fabric maintenance, modification and general maintenance work done, with a view to establishing a more sustainable operating model with offshore-onshore collaborations.

Working closely with the R2S project leads, BP ensured minimum impact on limited offshore accommodation (bed space). To complete the R2S virtual capture of assets, a high density of 360° spherical photographs was required. On the Magnus platform for example, over 7000 positions were photographically captured, to cover all areas required. A vivid, intuitive photographic walk around environment of each facility was then created using the spherical photography taken, built within the VAM software system. This provided the ability to place tags within the images to identify equipment, link to documents and databases, enabling users to search the virtual facility by tag number (Little, *et al.,* 2016). This enabled BP to show onshore employees a detailed view of the facility for context, reducing travel requirements and improving access to vital information. During this case study, a number of tangible benefits were realised largely due to the use of visual collaboration platforms, all of which could be readily transferred to construction. These included an immediate return on investment after deployment of the VAM system (the return amounted to over 20 times the initial deployment cost on this single renewal project alone, as noted in Little, *et al*., 2016). On the MLXP and ELXP project, BP further recorded a 10% improvement in planning and resource efficiency in the reducing of staff requirements in isolated sites, improved designs accuracy, more effective and efficient communication and collaboration between the different teams and expertise involved.

Case Study 3: Collaboration, Data Hub

The Magnus Life Extension Project and Eastern Trough Area Project Life Extension Project is further analysed in the context of developing a collaborative Data Hub. The VAM was applied as a central hub for a variety of systems also utilized in relation to a particular asset (Christie, *et al.,* 2015). Maintenance management systems (MMS), equipment management systems (EMS) and conditioning monitoring systems (CMS), for example, can all be linked within some VAM technologies. This creates a central point, a hub, for data that is held within disparate systems that relate to the same asset and thus presenting a significant opportunity and platform for collaboration. It also gives visual context to the data held within these systems that makes the information clearer to understand. Christie, *et al.,* (2015) explained that each task was tagged within the system with a corresponding symbol to identify the kind of job and then each work pack, which featured photography images from the VAM system, was attached to the tag. Visually this made it very easy to see the spread of tasks that were required within the campaign on the particular asset. The operator went a stage further to include the MMS data for each task within the corresponding tag on the VAM system. They then set up the tags to change colour depending on the criticality of the job, as dictated by the MMS. All of this planning and work pack creation was done from the office, using the VAM technology. What this provided was a highly visual representation of the maintenance campaign which assisted the operator to ensure that very urgent tasks were handled first and to ensure consistency across asset systems. This example shows how VAM technology can provide a collaborative environment for existing and future systems. The technology has also been shown to increase collaboration between operators and their contractors both in operations and the supply chain.

As mentioned, the measurement capability within VAM technology enables areas to be investigated and analysed without the requirement to physically visit the asset. Some operators have reported that they use their VAM technology to further advantage, in competitive bid situations. By allowing contractors/third parties to access the visualization of their asset, operators can receive accurate and competitive estimates for work without the expense and inconvenience of having additional visitors to their assets. This also enables the typically challenging bid process to be expedited and streamlined. Furthermore, equipment vendors have been given access to the visualizations of some operators' assets in order to discuss and identify issues with plant. Images, sound recordings and video can be added as tags in some VAM technology and this enables users to communicate faults with vendors as an initial step before a visit to the asset. In some cases this may mean visits to the asset to fix the faulty equipment are reduced.

DISCUSSION

Having instantaneous access to information at the right time and in the right format improves productivity, reduces costs and enables more effective decision-making (East 2016, Whyte and Lobo 2010, Leon *et al.,* 2015). The application and benefits of VAM detailed above could be significantly beneficial to the construction industry, particularly in terms of facilities management and operation of built assets (Bordat *et al.,* 2004, Love *et al.,* 2016, Adam *et al.,* 2017). Major infrastructure projects like underground mass transport systems, airports and tram systems are particularly becoming very complex and must accommodate several smart technologies and integrated systems in order to meet the demands of the 21st century in terms of security, energy usage, climate change and rapid population expansion. The PAS 1192-3 'Specification for Information Management' for operational management of an asset can for example be used with VAM to develop digital plan of deliverables, which can be specified in a contract and delivered using Construction Operations Building Information Exchange (COBie) (East, 2016).

We see increasing application of digitisation in the construction industry, and a desire to realise the aspirations of Integrated Project Delivery (IPD) with the consequential embracing of complexity in projects, promotion of understanding, support for visualisations and improved reliability. However, as with many new technologies, a great number of challenges and issues can occur, these related to collaborative challenges, to synchronous/ asynchronous communication and, most importantly, to tackling risks and uncertainty regarding costs and lack of on-site information. VAM systems, such as R2S, offer the potential to support a transfer of this knowledge to the built infrastructure and construction industries. Infrastructure projects are typically driven by tight budgetary constraints and high operational and maintenance costs. VAM can be used as a mechanism to capture the data needed to deliver a consolidated operations and maintenance manual, which can be imported directly into computerized maintenance management systems and asset management package. This could be a crucial step in 'future-proofing' critical infrastructure (Love *et al.,* 2017). Planned and unplanned shutdowns and system failures can now be efficiently and cost-effectively executed as all the requisite systems needed for these operations integrated into a single VAM platform.

CONCLUSIONS

VAM technologies applied during project initiation and early phases of projects in the O&G industry enabled asset familiarisation, reduced time spent on engineering surveys, reduced travel time to and from sites, problem solving platforms between onshore and offshore teams as well as reduced the disruption caused during engineering surveys. *VAM enhanced horizontal collaboration between operating and non-operating partners*, thus, saving on valuable time, since all involved stakeholders had access to a virtual model of the project and thus negating the need for site visits to isolated and often harsh weather environments in the North Sea. On the vertical supply chain axis, a highlighted feedback was that VAM provided subcontractors with no previous experience on specific tasks or sites, with the ability to visualise the work site and accurately plan the work without the requirement for a time consuming and costly visit. VAM application during the tendering process allowed contractors to provide a more accurate cost to their clients. Effectively, VAM application de-risks unknowns and surprises once onsite that could impact on work scope, time and billable costs.

Could VAM actually change our perception of IPD, collaborative projects delivery and facilities management? BIM and COBie have been welcomed pacesetters to the needed technological inputs that might help reduce some of the inefficiencies in the industry. Based on the evidence and benefits realised from the case studies presented from the O&G sector, the research suggests that VAM does indeed hold significant potential for construction infrastructure delivery and operation. The findings of the paper draw on three case studies and indicate significant potential for stepped change and learning opportunities in the way built assets are currently delivered and managed. Therefore, future research within this on-going research will focus on applications of VAM technologies on real-world infrastructure projects. These applications would intend to monitor group dynamics and collaborative practices when developing and encompassing as-built models within R2S, as well as the using VAM for operations and maintenance of infrastructure projects.

REFERENCES

Adam, A, Josephson, P-E B and Lindahl, G (2017) Aggregation of factors causing cost overruns and time delays in large public construction projects: Trends and implications. *Engineering, Construction and Architectural Management*, 24(3), 393-406.

Ahiaga-Dagbui, D, Love, P, Smith, S and Ackermann, F (2017) Toward a systemic view to cost overrun causation in infrastructure projects: A review and implications for research. *Project Management Journal*, **48**(2), 88-99

Arias, E G (1995) Designing in a design community: Insights and challenges. *Proceedings of DIS'95 Symposium on Designing Interactive Systems: Processes, Practices, Methods, & Techniques*, 259.

Bordat, C, McCullouch, B G, Sinha, K C and Labi, S (2004) An Analysis of Cost Overruns and Time Delays of INDOT Projects. West Lafayette, Indiana: Joint Transportation Research Program - Indiana Department of Transportation/ Purdue University [Publication FHWA/IN/JTRP-2004/07].

Bucciarelli, L L (1994) *Designing Engineers*. Cambridge, MA: MIT Press.

Christie, R, Fleming, C, Donnelly, B and Huff, S, (2015) How visualization technology is maximizing up time. *SPE Middle East Intelligent Oil & Gas Conference & Exhibition*, 15-16 September, Abu Dhabi, UAE.

D'Adderio, L (2001) Crafting the virtual prototype: How firms integrate knowledge and capabilities across organisational boundaries. *Research Policy*, **30**(9), 1409-1424.

Denzin, K N and Lincoln, Y S (2011) *The Sage Handbook of Qualitative Research 4th Edition*. Thousand Oaks, CA: Sage, 301-316.

East, B (2016) *Construction-Operations Building Information Exchange (COBie)*. National Institute of Building Science. Retrieved from http://bit.ly/2oLAUJF [7th April 2017].

Eastman, C, Teicholz, P, Sacks, R and Liston, K (2011) The future: Building with BIM. In: C Eastman, P Teicholz, R Sacks and K Liston (Eds.) *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. Hoboken, NJ: John Wiley and Sons, Inc, 351-389.

Eppler, M J and Burkhard, R A (2007) Visual representations in knowledge management: framework and case. *Journal of Knowledge Management*, **11**(4), 112-122.

Ewenstein, B and Whyte, J K (2007) Visual representations as 'artefacts of knowing'. *Building Research & Information*, **35**(1), 81-89.

Fischer, G (2000) Symmetry of ignorance, social creativity, and meta-design. *Knowledge-Based Systems*, 13(7-8), 527-537.

Fuggini, C, Manfreda, A, Andrés, J J Á, Pardi, L, Holst, R, Bournas, D A, Revel, G M, Chiariotti, P, Llamas, J, Gatti, G, Dvorak, M and Mariani, G (2016) Towards a Comprehensive Asset Integrity Management (AIM) Approach for European Infrastructures. *Transportation Research Procedia*, **14**, 4060-4069.

Gerring, J (2006) *Case Study Research: Principles and Practices*. Cambridge: Cambridge University Press.

Hobday, M, Davies, A and Prencipe, A (2005) Systems integration: A core capability of the modern corporation. *Industrial and Corporate Change*, **14**(6), 1109-1143.

Lawson, B (2005) *How Designers Think: The Design Process Demystified 4th Edition*. Amsterdam: Architectural Press/Elsevier.

Leon, M, Doolan, C D, Laing, R, Malins, J and Salman, H (2014a) Application of interactive surfaces to support computer mediated collaborative design environment. *Proceedings of the 18th International Conference on Information Visualisation*.

Leon, M, Laing, R, Malins, J and Salman, H (2014b) Development and testing of a design protocol for computer mediated multidisciplinary collaboration during the concept stages with application to the built environment. *Procedia Environmental Sciences*, **22**, 108-119.

Leon, M, Laing, R, Malins, J and Salman, H (2015) *Making collaboration work: Application of a Conceptual Design Stages Protocol for pre-BIM stages in BIM in Design, Construction and Operations*. Wessex, UK: WIT Press, 205-216.

Little, J, Fleming, C and Donnelly, B, (2016) Using a forensic tool to save bed space with visual planning. *Intelligent Energy Exhibition & Conference*, 6-8 September, Aberdeen, UK.

Lobo, S and Whyte, J (2017) Aligning and Reconciling: Building project capabilities for digital delivery. *Research Policy*, 46(1), 93-107.

Love, P E D, Ahiaga-Dagbui, D D and Irani, Z (2016) Cost overruns in transportation infrastructure projects: Sowing the seeds for a probabilistic theory of causation. *Transportation Research Part A: Policy and Practice*, **92**, 184-194

Love, P E D, Ahiaga-Dagbui, D D Welde, M and Odeck, J (2017) Light rail transit cost performance: Opportunities for future-proofing. *Transportation Research Part A: Policy and Practice*, **100**, 27-39.

Marquardt, W and Nagl, M (2004) Workflow and information centered support of design processes-the IMPROVE perspective. *Computers & Chemical Engineering*, **29**(1), 65-82.

Maslin, E (2013) North Sea renewal. *Offshore Engineer Magazine*, **10**(13), 58-61

Neumann, T and Krieger, J (2012) Innovative Monitoring and Evaluation of Ageing Infrastructure. *Proceedings of Civil Structural Health Monitoring Workshop (CSHM-4)*.

Oil and Gas Authority (2017) *Lessons Learned from UKCS Oil and Gas Projects 2011-2016*. The National Archives, London, UK.

Ozorhon, B and Cinar, E (2015) Critical success factors of enterprise resource planning implementation in construction: Case of Turkey. *Journal of Management in Engineering*, 31(6), p.04015014.

Pahl, G and Beitz, W (1995) *Engineering Design: A Systematic Approach 2nd Edition*. Berlin, Germany: Springer.

Poirier, E, Forgues, D and Staub-French, S (2016) Collaboration through innovation: Implications for expertise in the AEC sector. *Construction Management and Economics*, **34**(11), 769-789.

Schön, D (1991) *The Reflective Practitioner: How Professionals Think in Action*. London: Ashgate Publishing Limited.

Tezel, A, Koskela, L and Tzortzopoulos, P (2009) Visual management - A general overview. *Fifth International Conference on Construction in the 21st Century (CITC-V) Collaboration and Integration in Engineering, Management and Technology*.

Tjell, J and Bosch-Sijtsema, P M (2015) Visual management in mid-sized construction design projects. *Procedia Economics and Finance*, **21**, 193-200.

Whyte, J and Lobo, S (2010) Coordination and control in project-based work: Digital objects and infrastructures for delivery. *Construction Management and Economics*, **28**(6), 557-567.