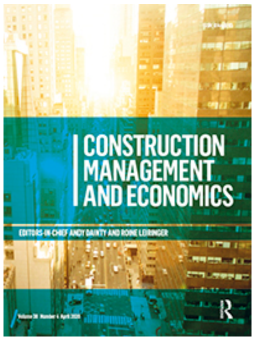

Construction Management and Economics

ISSN: 0144-6193 (Print) 1466-433X (Online) Journal homepage: www.tandfonline.com/journals/rcme20

Virtual design and construction

John Kunz & Martin Fischer

CONSTRUCTION MANAGEMENT AND ECONOMICS
2020, VOL. 38, NO. 4, 355–363
https://doi.org/10.1080/01446193.2020.1714068

Virtual design and construction

John Kunz and Martin Fischer

Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA

ABSTRACT
Virtual Design and Construction (VDC) is the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives. Professor Levitt's Virtual Design Team (VDT) project provided a fundamental point of departure of this work: the organisation model provides a central theoretical and practical element in the VDC framework. VDC models are virtual because they are computer-based descriptions of the project. This paper summarises the VDC framework that integrates an organisation perspective with perspectives that are implicit in VDT, including 3D Building Information Model (BIM) product models of a product to be designed, built and operated – typically a physical facility – management by objectives, Lean production management and the social method of Integrated Concurrent Engineering (ICE). Thus, VDC project models emphasise those aspects of the project that can be designed and managed, i.e., the product (typically a building or plant facility), the organisation that will define, design, construct and operate it, and the process that the organisation teams will follow. Many companies and hundreds of professionals now use VDC methods, and they consistently find that they improve project and business performance.

ARTICLE HISTORY
Received 12 December 2019
Accepted 5 January 2020

KEYWORDS
Building Information Models (BIM); collaboration; construction; design; metrics; organisation; process

Introduction

Facility development projects are increasingly complex, time consuming, of variable quality and expensive for their clients although sister industries such as aircraft manufacturing have had dramatic improvements in time, cost and quality performance. Project development is inherently complex, becoming more so because of technical, client and societal pressures. In addition, the slow adoption of new technology in construction has led to improvements that lag in comparison to many sister segments of the economy. A primary finding of our work after our years of development, teaching and its use in practice is that many organisations and clients around the world find enough value in improved cost, time, quality and safety from use of VDC methods that they support major and continuing investment in training and technology to bring these methods into broad and routine practice. We have taught VDC methods to our university students for two decades and, since 2008, taught the methods to many hundreds of professionals from multiple countries around the world who now use the methods routinely. We find that individual practitioners of many disciplines can effectively adopt and use VDC methods routinely given support and access to enabling technology, and they even enjoy do doing so.

Background

Early in the twenty-first century, the facility design-construction-operations process has many admirable properties. The AEC design-construction process creates the world's fixed physical wealth, such as homes, offices, schools, power plants, and fixed systems of our lives, including water, waste, transportation and power distribution. However, the process is fragmented and takes a long time to complete (usually far too long for the owner). The fixed wealth for basic facilities such as housing and transportation is expensive for all and increasingly so for the world's less advantaged. The theoretical frameworks in use and being taught in universities, including our own, did not show promise to address the fundamental problems of the design, construct, operate processes in the Architecture-Engineering-Construction (AEC) industry.

We introduced the term Virtual Design and Construction in 2001 as part of the mission and methods of the Centre for Integrated Facility Engineering (CIFE) at Stanford University (CIFE 2019a). Both of the authors used the VDC method in research and

CONTACT John Kunz kunz@stanford.edu Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94303, USA

teaching since 2001 (Kunz 2003) with almost all our recent Ph.D. students using VDC methods. After teaching the methods to many hundreds of professionals in project teams all over the world have implemented VDC. Companies now have made major strategic commitment to broad scale VDC use across their different offices and multiple projects in each office.

Virtual Design Team (VDT) and the work of Levitt

VDC would not have been possible in its current form without the inspired earlier work of Levitt, which provided a fundamental point of departure for this work. This section summarises major features of VDC inspired by work of Levitt.

Virtual is a key concept and a part of the name both of "Virtual Design Team" (Levitt *et al.* 1994, Jin and Levitt 1996, Kunz *et al.* 1998) and "Virtual Design and Construction." The Virtual design team is a generic computer model of design teams. Similarly, the process of Virtual Design and Construction is not an actual human-based design and construction project but a generic process to model and manage design and construction projects.

While VDC does not have the simulation-based prediction of VDT, VDT directly inspired the inclusion of the organisation as an explicit element of VDC. In addition, the observed and measured client and project performance metrics of VDC are inspired in concept and detail by the organisation team and task predictions of VDT as discussed in Levitt *et al.* (1999). VDT created and analysed a model of organisations, explicitly modelling the teams or individuals of a team, their specialties and some of their properties. Thompson (1967) viewed organisations as systems of interacting and interdependent parts, which VDT modelled formally as organisational actors, and VDC now models product, organisation, process and performance design and interactions explicitly. Inspired by Galbraith's (1977) framework that looks at organisational actors as information processing agents, the VDT framework predicts actor backlog, which the VDC method measures and reports as latency that one organisational actor experiences as wait time between making a request for information or a decision and receiving the requested information or decision. Measured team latency often had surprisingly strong correlation with predicted backlogs.

The VDT project developed and highlighted the crucial impact of task interdependency on project performance (Thomsen 1998), which led to the emphasis in the VDC framework on the representation and analysis of interdependency among the product, organisation and process (POP) and the ICE method, described below in the *Integrated Concurrent Engineering (ICE)* section, to identify, represent and model the sources and impacts of these interactions.

Levitt and Samelson's (1993) early work in safety included setting clear targets (i.e., zero incidents) and tracking and public sharing of actual performance. This emphasis on performance inspired inclusion of metrics in the VDC framework, including specification of target performance in identified key performance areas and project management based on consideration of measured or assessed actual performance in comparison with target values.

VDT and VDC both explicitly include templates that describe names and properties of organisational actors and tasks. Both VDT and VDC templates use templates to describe tasks with attributes such as task name and planned duration. The VDT organisation template includes properties including skill and size. Included within the production plan template, the VDC organisation template describes team responsibility and coordination-dependent teams, a concept whose importance derives directly from the crucial value of team backlog in VDT.

Our work is also strongly influenced by the currently popular idea of close university-industry collaboration, specifically through the community of the Centre for Integrated Facility Engineering (CIFE) at Stanford University (CIFE 2019a). CIFE was one of the first three centres at Stanford created in the Engineering school in 1988, created by Levitt, the dean of the school at the time, and some founding industry partners from around the world.

VDC theoretical framework

The VDC framework includes explicit specification of client and business objectives and measured performance for the project, project models that include models of the product, organisation and process, and explicit specification of project daily, weekly and milestone objectives and measured performance, as shown in Figure 1. In VDC, Integrated Concurrent Engineering (ICE), is the process in which representatives of the multidisciplinary own/design/build/operate teams work collaboratively over time to specify, create and check and apply the POP models and adjust them incrementally over the project lifetime based on the alignment between specified and measured client and project performance metrics.

Arrows in Figure 1 indicate flow of information over time among the elements of the VDC framework.

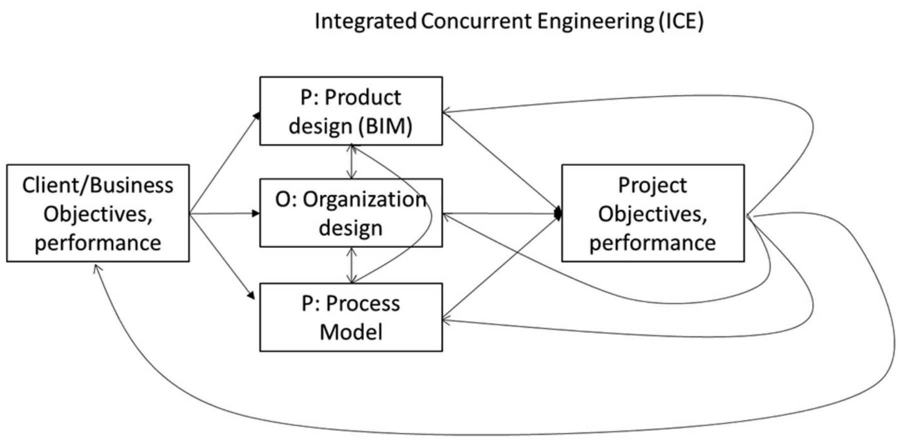

Figure 1. VDC framework includes explicit target and measured client/business objectives, Product design as a Building Information Model (BIM), Organisation design and Process models of the tasks to do design, construction, commissioning and operations. Informed by the client and project performance objectives, the project team specifies, builds, cheques and incremental revises the P, O, and P models, based on measured and target values of project objectives. These iterative Plan, Do, Check tasks take place in the multi-disciplinary Integrated Concurrent Engineering (ICE) collaboration process.

In general, each of the elements in the framework provides data to dependent elements to inform their design, work and evaluation. Data flow forward in time as the project progresses, and feedback loops enable constant updating of the product, organisation and process designs as the product, organisation and process models iteratively change over time as work gets done and the integrated team updates the P, O and P models based on assessment of the alignment of specified and measured performance metrics.

This section describes the elements of the VDC theoretical framework shown in Figure 1.

Client/business objectives, performance: client performance metrics

The VDC framework explicitly represents client metrics. Client metrics can and ideally do specify and represent life-cycle costs as well as project cost, schedule and safety, typically as judged by project participants using whatever method the project has available. Client attention to lifecycle costs is valuable since they dramatically exceed project costs. Client metrics concerning value describe and represent different measures of value for different client stakeholders such as users, operators and executives. It is often great value for clients to have a project team work with them to specify, measure, track and manage using these client metrics.

P: product design – 3D building information models (BIM)

A major enabling development in the past decade was emergence of technology and growing use of 3D Building "Information" Models (BIM) that describe the content – for example walls, windows, etc. and systems including structure, spaces and heating-air conditioning and ventilation – not just the geometry of the content as in line drawings and traditional CAD (BIM 2018), (buildingSMART 2013). Building Information Modelling (BIM) focuses on the building physical elements of the VDC model, which we find useful but limited because management issues usually involve building – organisation – process interactions. Bedrick (2005) discussed early promise of BIM in practice, and it is now entering wide use.

We encourage that broad teams specify BIM contents, check the accuracy and completeness of the BIM over time and use the BIM for their own work, such as engineering analysis, procurement, construction, commissioning and operations. Thus, VDC teams specify names of physical elements in their BIMs based both on their usual practice and, ideally, using names from a standard object specification. In addition, they specify important parameters and parameter values for defined entities, such as dimensions and materials for physical elements, skills, costs and capacity of teams and resources and budgets for tasks. BIM tools have entered wide use in the past decade and we strongly encourage their use to describe the names, properties including geometry and information necessary for procurement, construction and commissioning.

To specify a BIM and check that a BIM conforms to specification, we recommend use of a BIM template that includes attributes including task(s) to be performed using the BIM, BIM content: specific elements such as spaces, rooms, columns, beams, etc.

O: organisation design

Inspired by Levitt's Virtual Design Team (VDT) work (1994, 1999; Levitt and Kunz 2002) and also Jin and Levitt (1996) and Kunz *et al.* (1998), organisation and Process models describe the multi-disciplinary team, with responsibilities and budgets and individual tasks as described in production plans that project organisation teams plan and do to specify, design and engineer, procure, build and install, commission and operate the elements and systems of a facility.

Because of and with its focus on organisations, VDT implies but does not explicitly model or analyse the product on which the project team works. Partially to explore the impact of the project design itself on team performance and partially because, in many uses of VDT in practice, the details of the project were crucial influences on organisation and process performance, the VDC framework explicitly represents the physical product in templates and 3D BIMs. We also built on emerging work on concurrent engineering described by Prasad (1996) and integrated the VDT organisational perspective in the unified product – organisation – process framework of concurrent engineering.

P: process model of production management

Production management emerged as discussed in Shewhart (1931), Deming (1986). Along with the emergence of BIM, Lean production management and the Last Planner system have become important in practice in the past decade (Koskela 2002, Khanzode *et al.* 2006, LCI Israel 2015, Umstot and Fauchier 2017). VDC creates an integrated framework and set of methods to manage the project, including the Product, normally a building, the Organisation that designs, builds, commissions and uses the building and the design-construction Process, i.e., the POP model elements of Figure 1.

Lean continuous process improvement methods emphasise a cycle of Plan, Do, Check, Act (PDCA) steps (Shewhart, 1931, Deming 1986, PDCA 2019). Regarding the elements of VDC, project teams create PDCA plans for major segments of work, such as conceptual design, detailed design, construction planning, construction, commissioning and operations. Teams also create short-interval – from periods from a day to a week – PDCA production plans to generate designs, do procurement, construction, etc. We recommend that projects use the collaborative ICE process to define and follow a formal PDCA process to specify, create, check accuracy of and use BIMs of the product, design and performance of the organisational teams and process tasks over time.

For BIM, successful BIM teams use a PDCA process to manage the content and detail of the many evolving versions of BIMs to serve different project stakeholders over time. Specifically, use of BIM within VDC includes PDCA steps to specify (Plan), author (Do), Check and Act for each of the P, O and P project elements and their interdependencies.

For Organisation design and management, Plan steps specify; Do steps do the work of tasks; Check steps evaluate progress with respect to targets, and Act steps represent management interventions.

For metrics within VDC, PDCA steps specify target metrics and target values (Plan), measure and assess performance (Do), assess the believability of metric definitions, target values and measured/assessed values (Check), and take management steps based on target and measured values, celebrate and learn from good performance, and identify existence, causes and remediation methods for performance that is not so good (Act).

For Production management within VDC, PDCA steps Plan tasks for project teams and individuals. The individual teams and project participants do some work, which is then checked. Finally the next step in the plan can be started.

Project objectives, performance

VDC also explicitly includes organisational performance metrics and details of coordination commitments among explicitly specified organisational elements, and we find that VDC users consistently use these features. More broadly, as described by Drucker (2007) and Odiorne (1982), the process of management by objectives includes definition of explicit project outcome and incremental performance targets by the client and the development team, definition of responsibility for objectives, which often is shared, and frequent measurement of performance and management intervention based on differences between target and actual performance.

Project metrics

We find that teams pragmatically can and will define, manage and track about ten production metrics in some detail such as in this template, and they get value when they so. The on-time schedule completion percentage and product check result contribute directly to project schedule and quality metrics. Many teams also specify metrics for the conformance of budget (dollars and/or FTE-hours) to expenses and worker time spent on each task and define various measures of quality that can be assessed by project participants as the work progresses.

Outcome metrics specify performance to be reported by a project to internal corporate senior management, typically at the end of the job and often also monthly or quarterly. *Production* performance metrics are those that the team uses to measure and monitor work in order to assess and manage production, typically daily, weekly or perhaps monthly. Project metrics templates allow users to define their project metrics, target values and other crucial attributes.

Integrated concurrent engineering (ICE)

The fundamental inspiration for ICE was the extreme collaboration environment called Team-X as developed used by the Jet Propulsion Laboratory (JPL) (Mark 2002, Case 2015). JPL developed and has used this social method of interaction to develop and evaluate space mission concept designs. A design team of experienced flight-project engineers is co-located in at JPL to do architecture, mission, and instrument design studies extremely quickly – a few days, versus many months prior to adoption of this method. Team X celebrated its twentieth anniversary in 2015. The collaborative engineering takes place in a room with about twenty engineers, networked workstations, a supporting data management infrastructure, large interactive graphic displays, computer modelling and simulation tools, historical data repositories and a shared project model that the design team updates. At Stanford, VDC ICE sessions take place in a similar room with a similar multi-disciplinary team and similar enabling technology and similar methods to organise and run sessions (Chachere *et al.* 2004). Many company sites around the world now use ICE methods, either for sessions of a few hours to a few days or, in a "Big Room", for continuous collaboration (Lean Construction Institute 2015).

Interactive VDC enables dramatic reduction in query response latency, or the time between any stakeholder posing a question and having information with sufficient quality that it can be used to make a design or management decision. Questions can be formal Requests for Information (RFIs) or informal inquiries of fellow stakeholders. In addition, VDC enables dramatic reduction in decision response latency, or the time between a stakeholder asking management or the owner for a decision and receiving a go or no-to response with an explanation. We repeatedly and consistently see latency change from weeks and days to hours and even minutes in integrated design sessions (Chachere 2009).

ICE provides a method to bring project teams together to collaborate, specifically regarding the functional intent, current and planned designs and target, predicted and measured behaviours of the Product, design-construction Organisation and design-construction Process. We suggest that project teams use ICE sessions to plan and discuss project kick-off, major review, weekly and daily design and construction. The ICE sessions work best in a room with multiple computers, ideally with at least three projected screens that all participants can see simultaneously. It is important to plan the session agenda around description, analysis and evaluation of product, organisation and process issues as shown explicitly in models. The pre-session team can invite all relevant stakeholders to the sessions.

For ICE within VDC, a Production Management Plan step schedules ICE sessions for stated purposes, identifies disciplines and individuals to invite, homework assignments for participants and session logistics. An ICE session performs the Project Management Do and Check steps on the session process and. Since the P, D, C and A steps are typically responsibility of different team members, coordinating these steps is hard in practice, so the PDCA process adds consistency and clear expectations of all participants.

We encourage practitioners to invite all relevant stakeholders to ICE sessions such as one or more sessions for project kick-off meetings, including an owner representative, architect, major contractors, and a potential user. In the session, participants can identify the VDC models and visualisations for the project that will help stakeholders provide meaning and timely input to the project design and management. They also can define the project product, organisation and process vocabulary in a set of coarse level VDC templates as part of the kick-off meeting.

Integrated Concurrent Engineering sessions provide an effective and popular social method to do the model specification, check and use, which project teams around the world now routinely use as part of their VDC process.

Themes

VDC modelling and interaction methods enable practitioners to define and use shared explicit representations of the physical product (in the BIM and metrics) as well as the tasks and organisation (in the production plans). Properties to include in VDC models include geometry, cost, construction methods, etc. of product model elements, tasks, teams and metrics.

VDC models are virtual

As in VDT, VDC models are computer based, or virtual, so the *use* of VDC project models can be more interactive, flexible and visual than with paper-based methods. Authors of building, organisation and process models and schedules can share, discuss and show them to other stakeholders who can help make the use of the models directly or who have other responsibilities that may positively or adversely impact use of modelled project content in practice. Authors can project their BIMs and possibly project digital photos, ideally simultaneously with the schedule and organisation plan and metrics on each using separate projection screens. In this way, the project team can review and discuss integrated views of the project designs, plans and performance. Since VDC is designed to support multi-disciplinary project teams, appropriate stakeholders in the use of VDC include the multiple architects, engineers and general and multiple specialty contractors of AEC as well as owner representatives, users, suppliers, community representatives and when appropriate, representatives of government jurisdiction officials, groups that together form the project organisation.

Since VDC models are visual, project team members who have different professional vocabularies can all reference the same graphic models, providing support for the multi-cultural teams that are now common on many construction projects worldwide as well as some larger design teams. Many organisations around the world now use multi-disciplinary VDC models as the focus of daily, weekly and major milestone design, planning and review sessions.

VDC models represent the product, organization and process

VDC has the broad goal to create explicit models of those aspects of a project that a team can and must manage in order to meet explicit project objectives. A project manager can control three aspects of projects: the design of the *Product (P)* to be built, the design of the *Organisation (O)* that does the design and construction, and the design and the design-construction P*rocess (P)* that the organisation follows, which we describe as the POP framework. Because the project is inherently complex, it is crucial for teams to work to clarify assumptions, plans, and consequences of different stakeholders with different discipline specialties, experiences and values. Explicit models, specifically the BIM, summary of organisation team participants and the production plan, help this communication. In addition, checklists or relatively detailed templates can help VDC team stakeholders describe individual elements of the product, organisation and process of a project. VDC templates define individual aspects of POP project models. For example, the BIM content specification and management template specifies building elements such as Floors, Walls and Beams; the Organisation segment of the Production plan template specifies organisational groups, and the Task Commitments - production plan template specifies activities and milestones. Gawande (2009) describes the use and value of checklists in complex multi-stakeholder work including medicine, airline flight and construction.

The VDC templates specify information that is used in models of the product, organisation and process. In current practice, a product model for a project is often although surely not always represented in BIM. Inspired by the VDT object and attribute definitions in the VDT software system (Levitt *et al.* 1994, Jin and Levitt 1996, Kunz *et al.* 1998), VDC templates define the vocabulary that a company or partnership uses to do a kind of work, allowing a community of organisation professionals to define shared vocabulary that individual projects can customise as needed. Generic templates define P, O, P and metric entity names, attributes and dependency relationships among objects.

The product model, and hence the Product segment of the VDC templates, represents the physical components and systems of the building. Other VDC templates describe organisation entities that design, build use and operate the systems and components, as well as the activities and teams to do design, construction operations and facility use and metrics that describe performance and have associated target and measured or assessed values.

VDC maturity model

Some agencies now see the value and need for formal processes to specify, create, check and use BIMs to develop projects. For example, the Australian government defines “BIM process consistency” as the consistent use of proven methods, techniques, standards, templates, workflows and tools within and across the public sector, which improves the performance of BIM adoption and implementation (Australasian 2018). We see VDC as a demonstrated method to improve BIM process consistency.

We find that users implement VDC methods and practice in three distinct phases, each of which has its own value proposition, strategy for producing value and costs. Normally, organisations proceed sequentially through the steps in this maturity model. These steps contribute incrementally to the effectiveness of BIM process efficiency and its use across the multiple stages of project development.

Visualisation and metrics

In this first phase, project teams create models of the Product in 3D, ideally 3D BIM, possibly of the Organisation that performs design, construction and operations and often of the production management Process that organisational participants follow to do the design, construction and operations and management. In addition, teams often specify target values for both milestone and short-interval production metrics, collect and manage at least in part based on performance metrics, some of which may be predicted from models and are tracked at major milestones and periodically during the process. The results of the CIFE-CURT VDC use survey found that this stage is in common (although not yet widespread) use within the global AEC industry (Gilligan and Kunz 2007). For Visualisation to work well, all stakeholder organisations need to develop the competence to create and interpret the visual models, and many need to develop core competence to develop them, which requires a strategic investment in the methods and their use. Similarly, for Visualisation to work well for multiple stakeholders, multi-party collaboration contracts need at least to allow and ideally to incentivize data sharing, which may require strategic change in partnering arrangements.

In the Visualisation phase, projects routinely model and visualise the most expensive elements of the Product, Organisation and Process (POP) using BIM and some database to describe names and properties of teams and tasks. They use a social process among project stakeholders to integrate multiple VDC models and model versions, justify investment in VDC tools, methods and human resources based on the value proposition to the project, since this phase is (relatively) inexpensive and individual projects receive can significant benefit. Finally, effective visualisation helps clarify project objectives, values, responsibilities, designs and constraints because good visualisation enables many more stakeholders to participate in project review far more meaningfully than in routine practice.

Many companies and projects around the world now use VDC at this initial level.

Integration (computer based)

In this phase, projects develop computer-based automated methods to exchange data among disparate modelling and analysis applications reliably. Some vendors support data exchange among different applications using proprietary exchange methods, which often works well for those applications made by the particular vendor. The results of the CIFE-CURT VDC use survey find early evidence that some projects use computer-based integration of two or more applications (Gilligan and Kunz 2007). For Integration to work well, vendors need to agree on exchange standards, which may require a strategic commitment to support cross-vendor data exchange. Similarly, for Integration to work well for multiple stakeholders, multi-party collaboration contracts need at least to allow and ideally to incentivize data sharing, which may require strategic change in partnering arrangements.

In the Integration phase, projects share data meaningfully among Product, Organisation and Process models and analysis programmes using interoperation, i.e., reliable computer-based data exchange. In addition, they cannot justify investment in VDC tools, methods and human resources based on their project value proposition. Rather, the value proposition must support the firm, since this phase is (relatively) expensive and multiple projects must use the same methods for the investment to produce significant benefit.

Automation

In this phase, projects use automated methods to perform design/analysis tasks or to help build subassemblies in a factory. For Automation to improve construction process performance, project organisations normally need to dramatically change their processes to enable or perform more high-value design and analysis to enable less time, rework and waiting during construction. To support fabrication, the project needs to make the strategic commitment to support a partnering arrangement that includes capable partners. Automation requires Integration, and good visualisation helps make it work well.

In our experience with VDC users around the world, in the Automation phase, projects automate some aspects of routine design for Computer Numeric Control (CNC) manufacturing of assemblies for field installation. Normally, they cannot justify investment in VDC tools, methods and human resources based on their project value proposition. Rather, the value proposition must support a programme of projects or the firm. In general, they have potential for dramatic improvement in construction efficiency, safety, effectiveness and project duration.

Conclusions

The construction industry is well known for being slow to change. Now that Innovators have a number of years of experience with VDC, early adopters from all over the world have been through our VDC Certificate programme (CIFE 2019b) and an early majority of practitioners in some regions of the world use VDC routinely, we see that VDC use is now well along the Rogers (2003) innovation diffusion curve. Our experience and observation is that VDC adoption has engaged innovators and early adopters broadly around much of the world – i.e., globally, VDC is in the phase of early adopters – and in some regions, such as the US West Coast and Scandinavia, it is now in significant use by an early majority of all AEC project participants including architects, general and sub-contractors and owners, i.e., an early majority of projects use at least some VDC. The next few years we expect to see broadening the use of VDC both as new companies start to use it well and as larger companies use it more widely within their geographically and technically diverse operations. Theoretically, VDC integrates the established method of management by objectives with the complementary organisation framework of Professor Levitt and his team, recent increased use of 3D BIM product models, Lean production management, and the social process of Integrated Concurrent Engineering. The value of these methods together seems both dramatically higher than any alone and to have significant value in AEC practice.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Australasian BIM Advisory Board (ABAB), 2018. Available from: https://bim.natspec.org/images/NATSPEC_Documents/ABAB_BIM_Process_Consistency_Report_Final_12-11-2018.pdf [Accessed 17 October 2019].

Bedrick, J., 2005. BIM and process improvement. AECbytes, Viewpoint #20. Available from: http://www.aecpe.com/BIM%20and%20Process%20Improvement.pdf [Accessed 17 October 2019].

BIM: "Building Information Modeling", 2018. *Wikipedia*. Available from: https://en.wikipedia.org/wiki/Building_information_modeling [Accessed 17 October 2019].

buildingSMART, 2013. Industry foundation classes IFC4 official release. Available from: https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2/HTML/ [Accessed 17 October 2019].

Case, Kelly, 2015. Team-X. Available from: https://jplteamx.jpl.nasa.gov/ [Accessed 17 October 2019].

Chachere, J., Kunz, J., and Levitt, R., 2004. Obs*ervation, theory, and simulation of integrated concurrent engineering: grounded theoretical factors that enable radical project acceleration*, CIFE WP087. Available from: https://purl.stanford.edu/mt071hz7530 [Accessed 17 October 2019].

Chachere, J., Kunz, J., and Levitt, R., 2009. *The role of reduced latency in integrated concurrent engineering*, CIFE WP 116. Available from: https://stacks.stanford.edu/file/druid:bd089dx8723/WP116.pdf [Accessed 17 October 2019].

CIFE, 2019a. *Center for integrated facility engineering*. Available from: https://cife.stanford.edu/ [Accessed 17 October 2019].

CIFE, 2019b. *CIFE certificate program*. Available from: https://online.stanford.edu/courses/xvdc110-virtual-design-and-construction. [Accessed 17 October 2019].

Deming, W.E., 1986. *Out of the crisis*. Cambridge: The MIT Press.

Drucker, P., 2007. *The practice of management, Harper Row, 1954, revised edition*. Oxford: Butterworth-Heinemann.

Umstot, D. and Fauchier, D., 2017. *Lean project delivery: building championship project teams*. Anacortes, WA: Armchair ePublishing.

Galbraith, J.R., 1977. *Organization design*. Reading, MA: Addison-Wesley.

Gawande, A., 2009. *The checklist manifesto: how to get things right*. New York, NY: Henry Holt and Company.

Gilligan, B. and Kunz, J., 2007. *VDC use in 2007: significant use, dramatic growth, and apparent business opportunity*. Available from: https://stacks.stanford.edu/file/druid:bc641nk6928/TR171.pdf [Accessed 17 October 2019].

Jin, Y., and Levitt, R.E., 1996. The virtual design team: a computational model of project organizations. *Computational and mathematical organization theory*, 2 (3), 171–195.

Koskela, L.J., *et al.*, 2002. The foundations of lean construction. *In*: *Design and construction: building in value*. Oxford, UK: Butterworth Heinemann, 211–226.

Khanzode, A., Fischer, M., Reed, D., and Ballard, G., 2006. *A guide to applying the principles of Virtual Design & Construction (VDC) to the lean project delivery process*. Available from: https://stacks.stanford.edu/file/druid:bc980bz5582/WP093.pdf [Accessed 17 October 2019].

Kunz, J.C., *et al.*, 1998. The virtual design team. *Communications of the ACM*, 41 (11), 84–91.

Kunz, J., Levitt, R., and Fischer, M. 2003. *Management and leadership education for civil engineers: Teaching virtual design and construction for sustainability, CIFE Working

Paper #WP 079. Available from: http://purl.stanford.edu/vq141qm4960 [Accessed 19 December 2019].

LCI Israel, 2015. *Last Planner® system business process standard and guidelines*. Available from: https://www.leanconstruction.org/media/docs/chapterpdf/israel/Last_Planner_System_Business_Process_Standard_and_Guidelines.pdf [Accessed 17 October 2019].

Lean Construction Institute, 2015. *The mindset of an effective big room*. Available from: http://leanconstruction.org/media/learning_laboratory/Big_Room/Big_Room.pdf [Accessed 17 October 2019].

Levitt, R.E., and Samelson, N.M., 1993. *Construction safety management*. Hoboken, NJ: John Wiley & Sons.

Levitt, R.E., *et al.*, 1994. The virtual design team: simulating how organization structure and information processing tools affect team performance. *In*: K.M. Carley and M.J. Prietula, eds. *Computational organization theory*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Levitt, R.E., *et al.*, 1999. Simulating project work processes and organizations: toward a micro-contingency theory of organizational design. *Management Science*, 45 (11), 1479–1495.

Levitt, R., and Kunz, J. 2002. *Design your project organization as engineers design bridges, CIFE WP073*. Available from: https://purl.stanford.edu/bs801ts5508 [Accessed 17 October 2019].

Mark, G., 2002. Extreme collaboration. *Communications of the ACM*, 45 (6), 89–93.

Odiorne, G.S., 1982. *Management decisions by objectives*. Englewood Cliffs, NJ: Prentice Hall.

PDCA, 2019. *Wikipedia*. Available from: https://en.wikipedia.org/wiki/PDCA [Accessed 17 October 2019].

Prasad, B., 1996. Concurrent engineering wheels. *In: The RASSP digest* – Vol. 3. Available from: https://www.researchgate.net/publication/258840215_Concurrent_Engineering_Wheels [Accessed 17 October 2019].

Rogers, E., 2003. *Diffusion of innovations*. 5th ed. New York: Simon and Schuster.

Shewhart, W., 1931. *Economic control of quality of manufactured product*. Oxford, UK: Van Nostrand.

Thomsen, J., 1998. The Virtual Team Alliance (VTA): modeling the effects of goal incongruency in semi-routine, fast-paced project organizations, Ph.D. Thesis. Available from: https://gpc.stanford.edu/sites/g/files/sbiybj8226/f/thomsen1998.pdf [Accessed 17 October 2019].

Thompson, J. D., 1967. *Organizations in action: social science bases in administrative theory*. New York: McGraw-Hill.