Belsvik, M.R., Lædre, O., and Hjelseth E. (2019). "Metrics In VDC Projects." In: *Proc. 27th Annual Conference of the International. Group for Lean Construction (IGLC), Pasquire C. and Hamzeh F.R. (ed.)*, Dublin, Ireland, pp. 1129-1140. DOI: https://doi.org/10.24928/2019/0167. Available at: <www.iglc.net>.

METRICS IN VDC PROJECTS

Matilde Reinholdt Belsvik[1], Ola Lædre[2], and Eilif Hjelseth[3]

ABSTRACT

The Norwegian construction industry is far behind other industries when it comes to productivity. To improve productivity several contractors take advantage of methodologies such as Virtual Design and Construction (VDC). VDC is about streamlining projects in a Lean context with tools like Last Planner, ICE, BIM and metrics. Although few studies have been found on metrics in VDC projects, it appears evident that metrics are important for continuous improvement. However, selecting adequate metrics is challenging, as they can require more than they give in return.

The study answers three research questions; (1) "How are building design processes measured?" (2) "Which main design phase challenges can be resolved with metrics?" and (3) "Which metrics should be used in future VDC projects?"

The methods used have been a qualitative case study of a Norwegian contractor's first implementation of VDC, as well as personal interviews with experienced design managers.

The implication of the study is a list with six basic metrics for the building design processes of VDC projects, based on challenges in Norwegian construction projects. Seven additional metrics for continuous project improvement are also presented.

KEYWORDS

VDC, Metrics, Design management, Continuous improvement, Lean construction

INTRODUCTION

The Norwegian construction industry has seen a decrease in productivity of 10 % since year 2000 (Thodesen 2018). In response, several methodologies have been introduced to solve this issue.

VDC and metrics are two of these and many Norwegian contractors have begun implementing VDC in their projects to improve project efficiency (Fosse et al. 2017; Knotten and Svalestuen 2014). VDC is defined as "the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives" (Kunz and Fischer 2009). Metrics is also suggested as a methodology to

[1] M.Sc student, NTNU - Norwegian University of Science and Technology, Trondheim, Norway, + 47 982 07 858, matildeb@stud.ntnu.no

[2] Professor, dr.ing., NTNU - Norwegian University of Science and Technology, Trondheim, Norway, + 47 911 89 938, ola.ladre@ntnu.no

[3] Professor, PhD, NTNU – Norwegian University of Science and Technology, Trondheim, Norway, +47 952 66 100, eilif.hjelseth@ntnu.no

improve productivity. Not only are metrics important to evaluate project success but can be utilized for continuous improvement (Fischer et al. 2017).

In the literature there is a large amount of published material on metrics and measurements of construction projects (Chan and Chan 2004; Costa et al. 2006; Haponava and Al-Jibouri 2011; Hughes et al. 2004; Kang et al. 2014; Yeung et al. 2012). There is also a decent amount on VDC (Alarcón et al. 2013; Fosse et al. 2017; Garcia et al. 2004; Kam et al. 2013; Khanzode 2010; Khanzode et al. 2006; Kunz and Fischer 2009). However, an apparent knowledge gap exists on the topic of metrics and VDC combined. Within VDC, metrics is one of the main tools yet only a few papers have been published about it.

Contractors want to effectively include metrics in their implementation of VDC and need a list of standard metrics applicable to all VDC projects. A case study of a Norwegian contractor has therefore been conducted with the purpose of making a list of recommended metrics, based on the main design phase challenges of construction projects as well as suggested metrics from published literature.

In order to find metrics that can be used to continuously improve design processes in VDC projects, the following three research questions were developed and answered:

- RQ1: How are building design processes measured?
- RQ2: Which main design phase challenges can be resolved with metrics?
- RQ3: Which metrics should be used in future VDC projects?

Due to the limited time frame, this research has been limited to one Norwegian contractor, Betonmast, and their experiences with VDC and metrics. The focus has been on finding metrics for the design phase of construction projects.

METHOD

The research design of this report has been a qualitative case study of Norwegian contractor Betonmast and their implementation of VDC.

First a pilot case study was conducted, involving Drammen station Business Center (DBC), to document Betonmast's first implementation of VDC. Data was collected through five personal interviews and an observation in an ICE-meeting to get an understanding of the different elements of VDC and typical challenges with the implementation. Informants were selected from the design group, as they had the most hands-on experience with VDC from the DBC project. During the pilot case study, it was found that one of the biggest challenges in VDC projects is defining meaningful metrics, which laid the foundation for further research on metrics and VDC.

Following the pilot case study, six design managers of the same contractor were interviewed to identify challenges in the design phase of more traditional construction projects and to review a list of suggested metrics for future VDC projects. These suggested metrics were obtained through a literature review about metrics and VDC. The interviews were personal semi-structured interviews, with a goal of understanding how metrics are used today and how a Norwegian contractor can use metrics in their future projects. The informants were chosen for their involvement in Betonmast's VDC development work and also for their interest in learning and testing out new ideas and methodologies.

THEORETICAL FRAMEWORK

The theoretical framework is presented in three parts. The first part is about Virtual Design and Construction, with a paragraph about its relation to Lean Construction and common tools within VDC. The second part is about metrics, with general theory on metrics in construction projects followed by the third part, on metrics in VDC projects.

VIRTUAL DESIGN AND CONSTRUCTION

Virtual Design and Construction (VDC) was first introduced in 2001 by John Kunz and Martin Fischer through the Center for Integrated Facility Engineering (CIFE) at Stanford University. The framework is about project optimization by taking advantage of different time-efficient tools to achieve project goals and objectives (Jovik 2012). Kunz and Fischer (2009) define VDC as "the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives." The goal of VDC in the building design phase is to use these models to understand the complexity of a project and predict potential challenges before a large commitment of time or money is made to the project (Khanzode et al. 2006).

With the implementation of VDC a project can achieve Lean principles, and Lean as a framework can increase the effectiveness of VDC projects. Thus VDC and Lean have been argued by several researchers to go well together (Alarcón et al. 2013; Gerber et al. 2010; Khanzode 2010; Khanzode et al. 2006; Mandujano et al. 2015). Lean Construction with its background in Toyota's Lean Production is about adding value, reducing wasteful activities, improving flow and focusing on continuous improvement through benchmarking and metrics (Fosse et al. 2017).

Common tools used within and in combination with VDC include The Last Planner System of Production Control (hereafter Last Planner), Integrated Concurrent Engineering (ICE), Building Information Modelling (BIM), Model Maturity Index (MMI) and Metrics. Last Planner is a planning tool for project control with focus on stakeholder involvement, work flow control and value adding activities through pull planning and lookahead processes (Ballard 2000). ICE sessions are integrated and co-located meeting processes where different disciplines collaborate and make decisions as a team (Fischer et al. 2017), while BIM is the digital and visual representation of what the team is working on with information tied to each building object. BIM is important in ICE sessions to create communication and collaboration between stakeholders, and maturity indexes can be used to attach status to areas or objects in a BIM-model (Svalestuen et al. 2018).

METRICS

According to Bassioni et al. (2004) there are many performance measurement methods coexisting in the construction industry, such as Balanced Scorecard, just-in-time (JIT), benchmarking and activity-based management. Several studies have suggested parameters and models for performance indicators and benchmarking (Beatham et al. 2004; Chan and Chan 2004; Haponava and Al-Jibouri 2011; Hughes et al. 2004; Yeung et al. 2012). Based on a comprehensive literature review and three case studies Chan and Chan (2004) presented Key Performance Indicators (KPIs) for project success. The KPIs included objective measures like time, cost and accidents but also subjective measures like quality and satisfaction. Subjective attributes are important to avoid limiting a projects' success assessment to objective metrics (Hughes et al. 2004). A major challenge of KPIs is their product oriented focus, and that most KPIs are "lagging" indicators (Beatham et al. 2004), meaning they are used for post-project evaluation and comparison. Haponava and Al-Jibouri (2011) have proposed a generic system for more process-oriented KPIs in an attempt to address the existing KPIs' main shortcomings. Yeung et al. (2012) have compiled leading and lagging KPIs into a composite performance index (CPI) for benchmarking of construction projects in Hong Kong.

METRICS IN VDC PROJECTS

Metrics in VDC projects should not only be used to measure project outcome, but should be utilized throughout the whole project duration for continuous improvement of project processes (Knotten and Svalestuen 2014). According to Ahmad et al. (2016) lagging KPIs "are of no or limited use to the concurrent construction projects". Thus the metrics for VDC projects should mainly be active, or "leading", indicators.

Although metrics are more commonly seen in the construction phase, they can also be used to manage projects during the building design phase. Knotten et al. (2015) argue that metrics should be set up to control the quality of design and exchange of information. In a study by Hamzeh et al. (2009), on the Last Planner System metrics in design, it is shown how important it is to have "standardized production planning and control practices as proxies for performance measurement and process improvement". Using simple metrics in the design phase is effective to show the status of a project and can give an indication of where a project needs to pay attention (Knotten and Svalestuen 2014).

Fischer et al. (2017) claim that it is through metrics a project can achieve the project objectives. If put in a Lean framework, for example by the use of PDCA (Plan, Do, Check, Act), metrics can be used to continuously improve project performance. Typical metrics in VDC projects have been PPC (Percentage Plan Complete), meeting satisfaction, decision latency and amount of changes, as well as the project results in terms of cost and duration. However, the challenge is to define meaningful metrics that relate to the project goals and objectives (Fischer et al. 2017).

Several studies have reported on the advantages and limitations of VDC (Gilligan and Kunz 2007; Grindland 2017; Husby 2017; Kam et al. 2013; Olofsson et al. 2007; Redman 2017), yet few have suggested or discussed the most relevant metrics for continuous improvement in VDC projects. The main focus in previous reports has been on metrics for evaluation of the VDC implementation.

The existing literature on metrics in VDC projects is limited, but a small literature review has been conducted of sources related to metrics and VDC combined (Fischer et al. 2017; Fosse et al. 2017; Hamzeh and Aridi 2013; Knotten and Svalestuen 2014; Kunz and Fischer 2009). This paper assumes that the implementation of VDC includes modelling in 3D BIM, some sort of concurrent, co-located design process and a planning tool of the design process similar to Last Planner. The result is a list of suggested metrics for the building design phase of VDC projects, as presented in Table 1. This list is used for the analysis of the empirical results gathered in this study.

Table 1: Design phase metrics from the literature

Metric	Kunz and Fischer (2009)	Hamzeh and Aridi (2013)	Knotten and Svalestuen (2014)	Fischer et al. (2017)	(Fosse et al. 2017)
Percentage Plan Complete (PPC)	X	X	X	X	X
Tasks Anticipated (TA)		X		X	
Tasks Made Ready (TMR)		X		X	
Root causes			X	X	X
Response latency	X			X	
Decision latency	X				
Evaluation of meetings	X		X		X
Amount of quantity take-off (QTO) done in 3D-model vs drawings			X	X	
How many times the BIM was used to review alternative solutions			X		
QTO from 3D-model vs spent materials			X	X	
Meeting participation	X			X	
Clashes identified using 3D-model/clash trends				X	X
Amount of rework	X			X	
Requests for information (RFIs) on site due to design clashes	X			X	

RESULTS AND DISCUSSION

METRICS IN THE PILOT CASE STUDY

The case studied has implemented VDC in four elements; Last Planner, ICE, BIM with MMI and metrics, however the metrics were generally only apparent during the ICE sessions. These sessions were held every other week and involved all relevant stakeholders for the agenda. Usually this would include the contractor (Betonmast), client, architect and MEP-engineers. A representative from the contractor functioned as the facilitator.

During the ICE sessions the metrics used were PPC, meeting agenda achieved and root causes of absent or delayed design deliveries/tasks. The root causes were generally lack of capacity, priorities or unfinished tasks upstream that affected the present task. At the end of each session the design team would participate in a “plus/delta” discussion of positive elements of the meeting as well as “elements that could be improved”. They would also answer an anonymous survey about their own and other stakeholders’ preparation for the session, meeting effectiveness and relevance of the agenda.

The metrics were logged, but with varying effort. As a result, it was hard to find apparent trends to the measurements and to use them for future improvements. It would be more interesting to analyze the metrics if more results existed. The informants had different opinions on the value and purpose of metrics, as it was something new to most of them.

Project participants reported that metrics was one of the most challenging aspects of VDC, and selecting the correct metrics for continuous improvement of design processes was difficult. They were skeptical of metrics in general, as they feared the metrics could potentially be ineffective or require too much resources. Having too many and too complex metrics have been shown to potentially be time- and resource-consuming (Chan and Chan 2004). A further analysis on metrics in VDC projects was therefore requested.

METRICS IN BETONMAST

RQ1: How are the building design processes measured?

The building design processes have generally not been measured in Betonmast and consequently their experience with measurements is limited. Most measurements that have been done are focused on the construction phase and general project results. This includes measuring cost, schedule and HSE (Health, Safety and Environment), and finding solutions for occurring delays or expenses that exceed the budgeted cost. Thus they are mainly measuring product, not process.

Some informants have participated in other measurements, such as the counting of quality deviations, evaluation of meetings and time spent on meetings, and the use of simple actions like color-coding to emphasize lack of decisions.

Building design meetings have traditionally been conducted based on the report from each previous meeting, with no clear agenda other than to go through the bullet points on the report. This has led to little or no development on each task during meetings.

Several informants expressed that they lack the right tools to measure the building design processes. Presently they have "delivery plans" and "decision plans". These are plans for the last possible moment to deliver or decide something, and can mainly be used to measure whether or not the design process is on schedule. As seen in the theoretical framework there is a lot of literature on measurements. It is therefore unclear whether the informants lack the time to read published literature or the tools are not the kind of tools they are looking for.

Some of the informants also express that the Betonmast employees to an extent lack experience and understanding of the building design management and design processes. This could be related to many employees being more focused on production than design. However, to produce good design deliveries their understanding of the buildability and what is to be constructed is crucial. They emphasize the importance of managing the design process in an order that corresponds to the construction phase. If they are to use metrics in the design processes, they want simple metrics that contribute to continuous improvement.

RQ2: Which main design phase challenges can be resolved with metrics?

Based on several interviews the following challenges have been identified as the main challenges in the building design phase for the contractor:

- Lack of decisions, prerequisites or clarifications

- Designing with low buildability or low quality
- "Loops" in the design process with unnecessary rework because of lack of, late or changes in decisions, or unidentified interdependencies
- Stakeholders are not prepared for meetings
- Delayed design deliveries which delay construction
- Minimal understanding of, and respect for other stakeholders needs and/or interdependencies between disciplines
- Communication through email, and sometimes lacking responses
- Tasks at meetings are just discussed, not solved
- Designers prioritizing other projects
- Hard to make schedules for the building design process

These challenges are per now usually solved over time in Betonmast. They let time pass and find solutions as new challenges appear. Some challenges are solved by giving consequences to the stakeholder responsible for a delay or cost overrun, for example to the client for late or changed decisions. Other challenges have been met by following the delivery and decision plans, but it is hard to control and manage the quality of the design work before deadlines.

Most of the challenges are challenges that lead to rework. If designers are asked to start designing without the correct prerequisites they will have to make their own assumptions, which often leads to rework for themselves and other stakeholders. Additionally, if the designers are not communicating with the construction teams, they will potentially design with low buildability and cause loops in the design process.

Other challenges are related to meeting efficiency. Through the implementation of VDC there will be ICE-meetings (or something similar) where stakeholders make decisions and work to develop solutions together. These meetings can be measured, for example by looking at the amount of decisions made or tasks solved. Additionally, one can evaluate each stakeholder's participation, preparation and efficient time spent in the meeting.

When asked about which of the challenges can be solved through metrics, the informants often expressed a lack of belief in the effect of metrics. They were also worried that metrics would be very time consuming. However, if systems could automatically make measurements it would be beneficial. According to the informants, any implemented metric should contribute to making sure that all necessary design is decided before construction begins, to avoid rework on site and save both time and resources.

If metrics are to be used it is important that they are used diligently, and that they are in some ways standardized within the company so that projects can be compared.

RQ3: Which metrics should be used in future VDC projects?

The informants expressed different expectations for metrics in the building design phase. Some said they would not use metrics unless they were forced to or had been convinced of the advantages of metrics. Others already saw metrics as very necessary to continuously improve design processes.

From the assumption that Betonmast is interested in a standardized list of metrics for their future VDC projects, the informants produced suggestions of what they considered to be possible metrics. The most frequent suggestions were:

- PPC, Percentage Plan Complete
- TA, Tasks Anticipated
  - How many upcoming tasks were already anticipated and scheduled for the next week on the previous work plan?
- Metrics related to maturity levels of the BIM
  - Number of drawing revisions after maturity levels
  - Whether or not BIM is coordinated across trades
  - % of design that actually corresponds with the construction phase
- Root causes of delays or lack of deliveries
- Consequence (cost or time) of rework/loops
- Amount of changes or rework during building design
- Cost of meetings
  - Could the agenda have been solved differently or for less money?
- Evaluation of meetings
  - Questionnaire to evaluate stakeholder preparation and relevance of agenda
  - Plus/Delta
  - Time spent efficiently/inefficiently
- Cost of solutions vs budgeted cost
- Decision and response latency and decision stickiness

PPC and metrics related to maturity levels can all contribute to keep the project on track and visualize which stakeholders are delaying the project. Improving these metrics will increase design schedule control and delivery reliability. Evaluating TA will improve look ahead planning, by forcing stakeholders to anticipate their needs and interdependencies before upcoming tasks. Root causes are important to identify the trends in delays and loops, and each meeting should be evaluated on cost, relevance and efficiency.

Decisions from the client seems to be a reoccurring challenge and a bottle neck in many projects, thus decision latency and decision stickiness were suggested as metrics to evaluate client decisions.

Several of the suggested metrics correspond to metrics presented in the literature. The informants have suggested a few additional metrics to the ones found in the literature, such as Plus/Delta in meetings and decision stickiness. At the same time some metrics are missing, especially related to the BIM. QTO from 3D-models, using BIM to review alternative solutions and identifying clashes in BIM will all lead to fewer RFIs on site.

A challenging aspect of metrics is to encourage high quality solutions at the same time as metrics are visualizing each stakeholder's performance. Metrics will be a negative if the stakeholders compromise with quality of their work to achieve good metrics results. Nearly all the suggested metrics are related to productivity or efficiency of process, and do not directly take into account quality of the product. Therefore, it is important to align the metrics with client and project objectives.

CONCLUSION

Although only experiences from Betonmast have been researched, the results should be transferable to other contractors implementing VDC in their projects.

The recommended metrics for VDC projects are shown in Table 2. The metrics should correspond to project goals and objectives. Most of the VDC projects will be interested in simple metrics that continuously improve their project. These are listed in the column "Basic metrics for all VDC projects". Seven additional metrics are recommended for projects that have the resources to extend their evaluation and further project improvement, listed in the "Suggestions for supplementary metrics". The recommended metrics are based on the literature review ("L") and interviews ("I") with design managers from the contractor Betonmast.

The use of a model maturity index on the BIM is a prerequisite for some of the metrics. However, if a maturity index is not implemented, these metrics can relate to milestones in the design schedule and BIM based information exchange.

Table 2: Recommended Metrics

Basic metrics for all VDC projects	Suggestions for supplementary metrics
PPC, TA and TMR in meetings [%] (L+I)	Time spent doing QTO [hours] (L)
PPC for each maturity level [%] (L+I)	Cost of design loops [$] (I)
Number of clashes in BIM after reaching each maturity level [#] (L+I)	Construction cost due to design rework or delay [$] (I)
Evaluation of meetings [scale 1-4]	Cost of meetings [$] (I)
Root causes [#] (L+I)	Cost of solutions vs budgeted cost [$] (I)
Decision latency [hours] and stickiness [#] (L+I)	Correlation between decision stickiness and number and impact of design loops [%] (I)
	Amount of rework per discipline [hours] (L+I)

PPC (Percentage Plan Complete) should be measured for tasks at each meeting and for planned deliveries at each maturity level. As a continuation of PPC, **TA** (Tasks Anticipated) and **TMR** (Tasks Made Ready) should be measured, to improve control of the scheduling process and provide a more detailed look ahead plan. TA is the percentage of planned tasks for the next week that were already on the previous work plan, while TMR is the amount of planned tasks that are ready for the next week (Fischer et al. 2017). PPC and TA should be measured in correspondence to the formulas shown in Figure 1.

$$PPC = \frac{Completed\ tasks}{Planned\ tasks} * 100\% \qquad TMR = \frac{Tasks\ ready\ for\ next\ week}{Total\ tasks\ for\ next\ week} * 100\%$$

$$TA = \frac{Tasks\ planned\ for\ next\ week\ on\ previous\ work\ plan}{Total\ tasks\ for\ next\ week} * 100\%$$

Figure 1: Formulas for PPC, TMR and TA

Number of clashes in BIM after reaching each maturity level should be measured to indicate and control the quality of the design. This number will visualize the importance of designing in correct order and doing proper controls before each maturity level.

Evaluation of meetings should be done after each ICE session to evaluate the stakeholders' perceived efficiency of the meeting, their preparation and the relevance of the agenda. This could be done using an anonymous questionnaire rating each question on a scale from 1-4, with 4 being the best score. Additionally, a discussion should be conducted of "plus/delta". Pluses are positive aspects of the meeting and deltas are areas of improvement. This metric can be used to improve meetings.

Root causes for lack of or delayed deliveries or decisions, as well as clashes in BIM should be tracked. The number of appearances of each root cause should also be tracked. Typical root causes could be lack of prerequisites or work capacity.

Decision latency (the time from a decision is requested until the client or relevant stakeholder makes a decision) and **decision stickiness** (the number of changes on the same decision) commit the client to making efficient decisions. These metrics require the client to be involved in design processes and evaluations of design. Decision stickiness is also a metric to avoid ambiguity in decisions.

Other suggested metrics include time spent doing QTO (Quantity Take-Off), cost of design loops, construction cost due to design rework or delay, cost of meetings, cost of solutions vs budgeted cost, correlation between decision stickiness and number and impact of design loops and amount of rework per discipline. These metrics are more difficult to measure and require more resources. It is uncertain whether the benefits are worth the effort, but these metrics are believed to be beneficial for continuous improvement. Many of them, such as cost due to design rework and cost of design loops visualize the economic potential of having good design processes.

The empirical results come from researching one Norwegian contractor's experiences with the building design phase and one VDC project. To make the list of suggested metrics more generalizable, more contractors and more projects can be studied. A study of metrics used in the following phases of construction projects can be done to identify metrics suitable for the full VDC project duration.

REFERENCES

Ahmad, S. B., Svalestuen, F., Andersen, B., and Torp, O. (2016). "A review of performance measurement for successful concurrent construction." *Procedia-Social and Behavioral Sciences*, 226, 447-454.

Alarcón, L., Mandujano, R., Maria, G., and Mourgues, C. "Analysis of the implementation of VDC from a lean perspective: Literature review." *Proc., IGLC*.

Ballard, H. G. (2000). "The last planner system of production control."PhD-thesis, University of Birmingham.

Bassioni, H. A., Price, A. D., and Hassan, T. M. (2004). "Performance measurement in construction." *Journal of management in engineering*, 20(2), 42-50.

Beatham, S., Anumba, C., Thorpe, T., and Hedges, I. (2004). "KPIs: a critical appraisal of their use in construction." *Benchmarking: an international journal*, 11(1), 93-117.

Chan, A. P., and Chan, A. P. (2004). "Key performance indicators for measuring construction success." *Benchmarking: an international journal*, 11(2), 203-221.

Costa, D. B., Formoso, C. T., Kagioglou, M., Alarcón, L. F., and Caldas, C. H. (2006). "Benchmarking initiatives in the construction industry: lessons learned and improvement opportunities." *Journal of Management in Engineering*, 22(4), 158-167.

Fischer, M., Khanzode, A., Reed, D., and Ashcraft, H. W. (2017). *Integrating project delivery*, John Wiley & Sons Inc., Hoboken, N.J.

Fosse, R., Ballard, G., and Fischer, M. "Virtual design and construction: Aligning BIM and lean in practice." *Proc., 25th Annual Conference of the International Group for Lean Construction, IGLC 2017, July 9, 2017 - July 12, 2017*, The International Group for Lean Construction, 499-506.

Garcia, A. C. B., Kunz, J., Ekstrom, M., and Kiviniemi, A. (2004). "Building a project ontology with extreme collaboration and virtual design and construction." *Advanced Engineering Informatics*, 18(2), 71-83.

Gerber, D. J., Becerik-Gerber, B., and Kunz, A. "Building information modeling and lean construction: Technology, methodology and advances from practice." *Proc., Proc. 18th Int'l Group for Lean Const*, Citeseer.

Gilligan, B., and Kunz, J. (2007). "VDC use in 2007: significant value, dramatic growth, and apparent business opportunity." *TR171*, 36.

Grindland, O. (2017). "Virtual Design and Construction - Implementering og effekter." NTNU.

Hamzeh, F., and Aridi, O. Z. "Modeling the last planner system metrics: A case study of an AEC company." *Proc., Proceedings of the 21st Annual Conference of the International Group for Lean Construction IGLC, Fortaleza, Brazil*, 599-608.

Hamzeh, F. R., Ballard, G., and Tommelein, I. D. "Is the Last Planner System applicable to design?—A case study." *Proc., Proceedings of the 17th Annual Conference of the International Group for Lean Construction, IGLC*, 13-19.

Haponava, T., and Al-Jibouri, S. (2011). "Proposed system for measuring project performance using process-based key performance indicators." *Journal of management in engineering*, 28(2), 140-149.

Hughes, S. W., Tippett, D. D., and Thomas, W. K. (2004). "Measuring project success in the construction industry." *Engineering Management Journal*, 16(3), 31-37.

Husby, H. (2017). "Virtual Design and Construction i prosjekteringsprosessen - Videreutvikling og forbedring." NTNU.

Jovik, L. T. (2012). "Tilrettelegging for god ICE-prosjektering." *Facilitation for improved ICE design*, F. O. Drevland, ed., Institutt for bygg, anlegg og transport, Norges teknisk-naturvitenskapelige universitet.

Kam, C., Senaratna, D., McKinney, B., Xiao, Y., and Song, M. (2013). "The VDC scorecard: Formulation and validation." *Center for Integrated Facility Engineering: Stanford University*.

Kam, C., Senaratna, D., Xiao, Y., and McKinney, B. (2013). "The VDC scorecard: evaluation of AEC projects and industry trends." *CIFE, Maharashtra, India*.

Kang, Y., Dai, J., Mulva, S., and Choi, J. "The 10-10 performance assessment campaign: New theories regarding the benchmarking of capital project performance." *Proc., Construction Research Congress 2014: Construction in a Global Network*, 2335-2344.

Khanzode, A. (2010). "An integrated, virtual design and construction and lean (IVL) method for coordination of MEP." *Unpublished Technical Report*, 187.

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." *CIFE, Stanford University, Palo Alto, CA*.

Knotten, V., and Svalestuen, F. "Implementing Virtual Design and Construction (VDC) In Veidekke–Using Simple Metrics To Improve The Design Management Process." *Proc., IGLC*.

Knotten, V., Svalestuen, F., Hansen, G. K., and Lædre, O. (2015). "Design management in the building process-a review of current literature." *Procedia Economics and Finance*, 21, 120-127.

Kunz, J., and Fischer, M. (2009). "Virtual design and construction: themes, case studies and implementation suggestions." *Center for Integrated Facility Engineering , Stanford University*.

Mandujano, R., Maria, G., Alarcón, L., Kunz, J., and Mourgues, C. (2015). "Use of virtual design and construction, and its inefficiencies, from a lean thinking perspective."

Olofsson, T., Lee, G., Eastman, C., and Reed, D. (2007). "Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing."

Redman, A. (2017). "Bruk av VDC og 4D i Skanska-prosjekter - Innføring av 4D-modellering i eksisterende VDC-rammeverk." F. O. Drevland, and R. Fosse, eds., NTNU.

Svalestuen, F., Knotten, V., Lædre, O., and Lohne, J. (2018). "Planning the building design process according to Level of Development."

Thodesen, S. (2018). "Produktivitetsfall i bygg og anlegg." <https://www.ssb.no/bygg-bolig-og-eiendom/artikler-og-publikasjoner/produktivitsfall-i-bygg-og-anlegg>. (11.02, 2019).

Yeung, J. F., Chan, A. P., Chan, D. W., Chiang, Y., and Yang, H. (2012). "Developing a benchmarking model for construction projects in Hong Kong." *Journal of construction engineering management*, 139(6), 705-716.