CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

The VDC Scorecard: Evaluation of AEC Projects and Industry Trends

By

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The VDC Scorecard: Analysis of Industry Trends from 108 Applications on AEC Projects

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Abstract

The VDC Scorecard was created to provide AEC professionals with a holistic, quantitative, practical and adaptive approach to evaluate and track VDC performance. The scoring covers the four major Areas of VDC Planning, Adoption, Technology and Performance, and the overall score is measured on a percentage scale that reflects the project performance relative to the industry's practice. As current research is primarily based on case-studies and anecdotal findings, data-based understand of VDC performance and related factors is a major drawback. Hence, the motivation for this paper was the need to understand evolving VDC performance and adoption patterns, based on a verifiable data-collection.

CIFE researchers have compiled a data-collection of 108 unique project cases, and over 150 VDC Scorecard evaluations. These pilot projects from 13 countries are diverse in facility type, contract type, delivery method, duration, and project phase during which the evaluation is conducted. This paper will explore the distinctive correlations, trends and patterns exhibited by the 108 pilot projects and critical findings on common VDC practices that enhance or hinder project performance. Statistical analysis of the scoring results was used in establishing correlations between the VDC Scorecard Areas and sub-Areas, termed as Divisions.

The primary results are related to the importance of, the formalization of VDC among project stakeholders, establishment of qualitative and quantitative objectives, involvement of stakeholders in early project phases, level and number of VDC applications use, appropriateness of model Level of Development, tracking and fulfillment of VDC objectives and the project teams' attitudes toward VDC. Performance wise, the top performing projects (top 25%) had 84% of its stakeholders involved in BIM/VDC opposed to just 35% with respect to poorly performing projects (bottom 25%); 83% of the top performing projects (top 25%) had established quantifiable objectives opposed to 3% for poorly performing projects (bottom 25%). Industrial construction projects had the highest average VDC score (63%), while urban-planning projects had the lowest average VDC score (37%).

Keywords: Virtual Design and Construction, Benchmarking, Key Performance Indicators, Planning

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1. Introduction

Virtual Design and Construction (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). Over the past 10 years, VDC processes and tools have gained popularity in the architecture, engineering, and construction (AEC) industry. The benefits of VDC are widely recognized as enabling more efficient multidisciplinary coordination and adding value to projects over their life cycles. The process of Building Information Modeling (BIM) that facilitates VDC has also gained dramatic adoption in industry over the past years, increasing from 17% in 2007 to 71% in 2012 (McGraw and Hill 2009, 2012). The ability to carry on VDC and BIM projects has also become an important attribute for AEC companies to be ahead of the market competition and undertake modern design and construction projects.

The current application of VDC and BIM in many projects is in an ad-hoc fashion (Khanzode, 2010), in which project teams are only motivated to develop and select methods and processes when trying to achieve certain desired results. Uncertainty towards the cost-benefit outcome of VDC also remains within the industry (Cassidy, 2012). In order to verify the outcomes related to VDC application that have already been recognized, identify the critical activities that lead to successful project delivery and investigate the potentials toward leveraging the industry’s overall performance, the research team at the Center for Integrated Facility Engineering (CIFE) at Stanford University has been establishing a quantitative measure based system, the VDC Scorecard, for AEC professionals to evaluate track and monitor the performance and outcomes of AEC projects.

The VDC Scorecard was created in 2009 by the researchers at CIFE based on previous related studies, including at least 22 formal papers regarding the application of VDC on single projects since 1995 and 23 notable VDC-related guidelines targeted at the enterprise or industry level (Gao, 2011). The Virtual Design and Construction Scorecard was designed, building upon points of departure from other research institutions and industry partners in the building industry, such as the Leadership in Energy and Environmental Design, and the Comprehensive Assessment System for Built Environment Efficiency, as well as evaluation frameworks and scoring systems adopted by other industries such as, Balanced Scorecard, Credit Score, The Michelin Guide and Wine Scoring (Kam, Senaratna, McKinney & Xiao, 2013). Over the past three years, the VDC Scorecard has evolved along with the growth of technology integration and the industry’s level of VDC practice.

Through the end of 2012, the CIFE research team has scored 108 unique AEC projects using the VDC Scorecard. The scoring results of these projects are analyzed using statistical approaches in order to establish correlations between practices and outcomes as well as to benchmark the current industry’s VDC performance. The findings of the scoring results are important in demonstrating the advantages and limitations that VDC brings to the realization of integrated design and project delivery, as well as its influences toward effective interdisciplinary corporation and project quality. The findings will serve as a preliminary reference tool in addition to the other existing literatures for project teams to implement BIM and VDC. This paper focuses on documenting the critical findings of the VDC scorecard research. Information regarding the formulation and development of the VDC scorecard and its user instructions is detailed in the Formulation and Validation of the VDC Scorecard (Kam, Senaratna, McKinney & Xiao, 2013).

2. Motivation

The motivation for this paper was the need to understand evolving VDC performance and adoption patterns, based on a verifiable data-collection. Data-based understand of VDC performance and related factors is a current drawback.

2.1. Data-based understanding of VDC performance

Incumbent studies regarding the planning, adoption, technological use and performance of VDC, is primarily based on anecdotal or case-study related evidence. The major limitations of using only a few case-studies are the inability to validate and generalize results as well as uncertainties regarding its reliability (Flyvberg, 2005). Therefore the insights and decisions based on anecdotal learning only, will not be as strong as making decisions that are also supported by statistically established insights. However, the research carried out on the VDC Scorecard, has enabled CIFE researchers to formulate a rare collection of 108 unique projects. The primary motivation of this paper is understand the correlations between the various VDC performance factors and relate these results to case-study based observations and hypotheses. Using the current VDC Scorecard vocabulary, a total of 51 unique correlation-pairs were observed, 6 VDC Scorecard Area-based correlations and 45 VDC Scorecard Division-based correlations.

2.2. Need to understand evolving VDC performance and adoption trends and patterns.

Present VDC Scorecard insights and recommendations are based on independent analysis of the VDC Scorecard cases. For example, if a certain Area and Division in the VDC Scorecard scored poorly with regards to expert-based benchmarks, feedback is given without considering the correlations between or within VDC Scorecard Areas, Divisions nor individual measures. However, analysis of correlations, using statistical techniques such as the Pearson's Correlation Coefficient and Spearman's Correlations Coefficient, resulted in unusual findings and relationships between the VDC Scorecard Areas, Divisions and Measures. Therefore, this paper was further motivated by the importance of understanding and analyzing these relationships, at the level of the VDC Scorecard Area and Divisions.

3. Methodology

3.1. The VDC Scorecard Methodology

The VDC Scorecard measures project performance in four major Areas: Planning, Adoption, Technology and Performance. These four Areas are further broken down into ten Divisions, and under each Division there are 56 detailed practice measurements in total in the most recent version of the Scorecard.

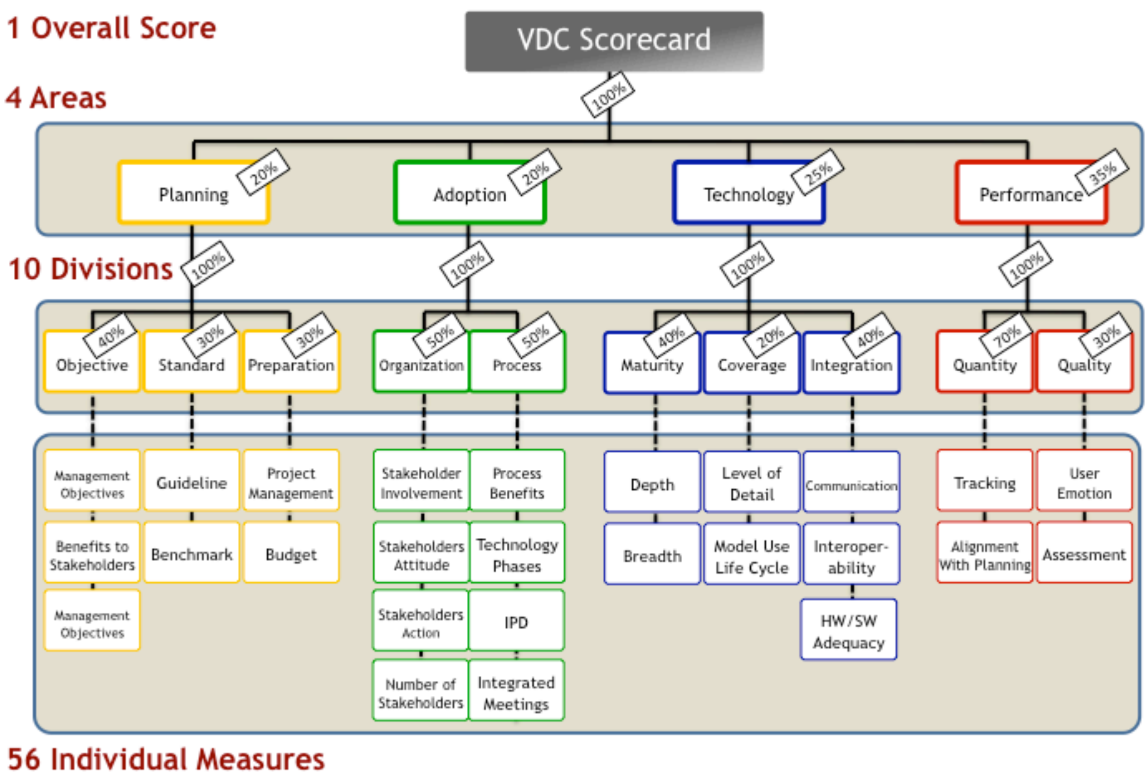

Figure 1. VDC Scorecard Evaluation Framework (see Kam, Senaratna, McKinney & Xiao, 2013 for complete list of 56 measures). The 10 Division scores are created using the 56 individual measures, in turn the 4 Area scores are created using the 10 Division scores and finally the total VDC score is created using a weighted sum of the 4 Area scores.

The four Areas constitute the organizing structure of the VDC Scorecard.

- Planning: This Area aligns defined quantitative and qualitative project objectives with desired business outcomes, and to identify standards, technologies, and resources that will be relevant to the project.
- Technology: This Area evaluates the models and analyses employed by assessing the maturity of the model uses, the level of detail of models across project phases, and the success of integration across technologies.
- Adoption: This Area assesses the organizations and processes involved in VDC by evaluating the success in aligning stakeholders' talents, motivations, incentives, and business structures to create integrated teams and processes that support the project objectives across all phases of the project.
- Performance: The attainment of project objectives is assessed both quantitatively and qualitatively.

Each measurement is quantified into a 'score,' which is then weighted and summed with other measurement scores based on the evaluation framework (Figure 1) to produce the total overall score of a project. The scoring is based on a percentage system where each project will be assessed against the industry norm and converted into an industry percentage ranking.

Like other survey-based assessments, these scores are subject to a number of potential sources of error. Such sources include, but are not limited to respondents' bias towards affirmation, atypical respondents, and insufficient interview time. To account for this, the scorecard also includes a measure of the confidence level, which also employs a percentage-based system.

Survey Process and Data Collection:

The survey method of the VDC Scorecard attempts inputs from all project stakeholders with all experience levels. These inputs provide more holistic information on the project performance from various perspectives. Scoring and interviewing is carried out via, phone interview, web-conferencing, email-follow-ups and personal interviews. The average interviewing time taken for the Express Version was 4 hours, and in over 70% of the projects scored, at least both the Architect and the General Contractor were interviewed.

CIFE researchers and students who enrolled in CEE 212 and CEE 259 at the Department of Civil and Environmental Engineering of Stanford University from 2009 to 2012 carried out the current data-collection. As of 2012, CIFE researchers have a comprehensive data-collection of 108 unique projects, and over 150 completed VDC Scorecards, scored by different researchers related to these projects.

3.2. Statistical Techniques

Correlation tests were carried out to observe differences within and in-between, continuous variables and categorical variables. The Pearson's Correlation, Spearman's Correlations, and Kendall's Tau (Agresti, 2010), were used to analyze the significance of the correlations between continuous variables such as Area and Division scores. Fisher's tests and Chi-squared tests (Agresti, 2010), were used to analyze the significance of the correlations between categorical variables.

4. The Data: 108 Projects

The projects evaluated by the VDC Scorecard are active AEC projects with various characteristics. They cover a wide range of facility types (Table 1). They are distributed across the world in 13 different countries in North America, Europe and Asia and 15 states across the US, and are designed and constructed by AEC firms in various regions. Delivery methods used by these projects range from the more conventional design-bid-build to the more integrated methods such as integrated project delivery (IPD) and integrated form of agreement (IFoA) (Table 2). They are also evaluated during different project phases from pre-design to the end of construction and close out (Table 3). The diversity in project features provides the confidence in generalizing the scorecard findings of the 108 projects to represent the practice of all AEC projects. It also provides data for cross comparison from which more focused performance strategies can be created.

Table 1. Percentage of projects by facility type.

Facility Type	Percentage of Projects
Courthouse	2%
Educational	9%
Entertainment	14%
Healthcare	13%
Industrial	2%
Infrastructure	5%
Laboratory	6%
Mixed-use	5%
Office	19%
Residential	15%
Urban Planning	2%
Other	3%

Table 2. Percentage of projects by project phase

Delivery Method	Percentage of Projects
Design-Bid-Build	35%
Alternate	51%
IPD	14%

Table 3. Percentage of projects by delivery method

Phase	Percentage of Projects
Pre-Design	5%
Schematic Design	4%
Design Development	10%
Construction Document	3%
Construction	46%
Closeout	5%
O&M	28%

The scorecard evaluations were completed based on project documents provided by the project teams as well as interviews with one or more project team members. The reliability of the scores is accounted by the 'confidence level' (Kam, Senaratna, McKinney & Xiao, 2013).

4.1. Distribution of the VDC Scorecard results

The average overall score of the 108 projects is 50%, which is exactly the mean of the score distribution. The average overall score is 50%, which is a weighted average of 4 VDC Scorecard Areas with 50% in Planning Area, 56% in Adoption Area, 48% in Technology Area and 47% in Performance Area. Of the 108 projects, 2 scored below 25% and are categorized as 'Conventional Practice'; 49 scored between 25% and 50% and are categorized as 'Typical Practice'; 52 scored between 50% and 75% and are considered 'Advanced Practice'; 5 scored between 75% and 90% and are considered 'Best Practice'; no projects scored between 90% and 100%, which would make them 'Innovative Practice' (Table 4). The score distribution suggests that VDC application is commonly used in AEC industry, but is not yet adapted as a prominent tool to facilitate AEC projects. Table 4 depicts that there are a few projects that have obtained Innovative Practice within the 4 Areas of Planning, Adoption and Technology. However, none of the 108 cases obtained Innovative Practice overall. Trends in the industry show that projects focus on spending resources for innovation in a particular Area of VDC. It is easier to innovate within a specific Area, than across measures in all Areas. The VDC Scorecard attempts to motivate decision-makers to apply their best methods across all measures and hence, to obtain a balanced and holistic assessment of VDC in their project.

Table 4. Score distribution of 108 AEC projects

	Range	Overall	Planning	Adoption	Technology	Performance
Innovative	90-100%	0	1	5	1	0
Best	75-90%	5	5	9	6	10
Advanced	50-75%	52	48	61	45	39
Typical	25-50%	49	50	30	44	46
Conventional	00-25%	2	4	3	12	13

The projects located in the US generally score higher than those outsides the US (Figure 2). This is due to the fact that the US has been leading the effort of VDC applications, and more stakeholders from the US than those from the other countries are incentivized to use VDC for their projects. However, the development of VDC in European and Asian countries can also be seen as many project participants start to realize the vast benefits it leads to. A design team of a European project expressed that the collaboration between stakeholders is critical to the realization of their design ambitions, and this level of collaboration was only enabled by the use of BIM model and communication technologies (Hong Kong BIM Awards, 2011).

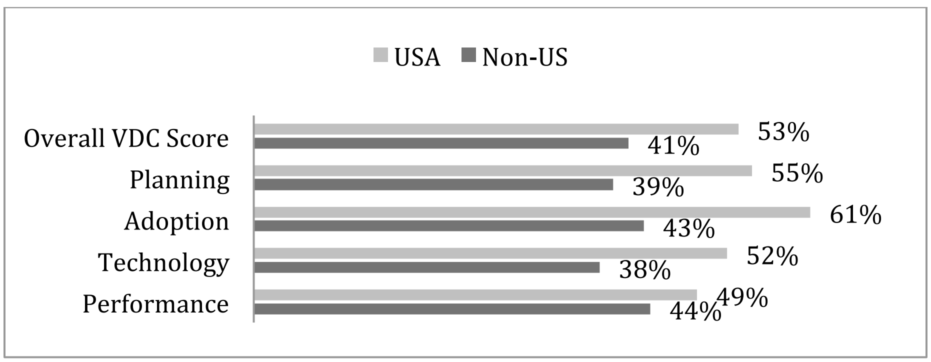

Figure 2. Cross comparison in overall and Area scores between projects by geographic location.

It is also found that entertainment, healthcare and industrial projects have scored 3% - 10% higher than the rest of the facility types (Figure 3). CIFE researchers find that the complexity and higher demand toward serviceability of these types of projects require more efficient collaboration between the project stakeholders in order to achieve design objectives. For healthcare projects, higher level of regulation and more specific code requirements also call for integrated delivery methods to facilitate more efficient design and construction.

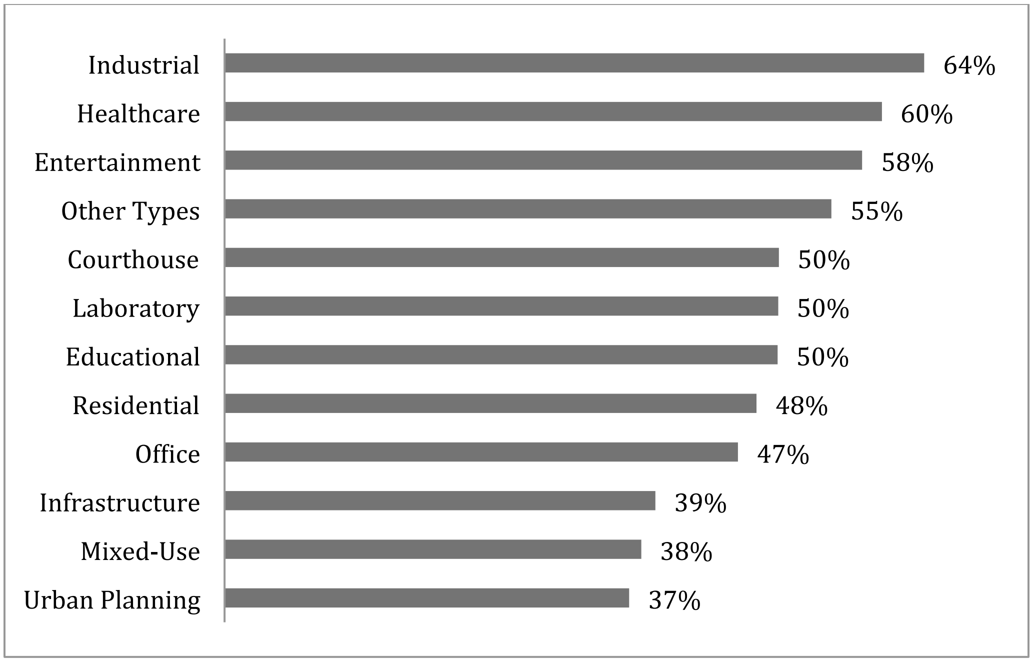

Figure 3. Average overall score by facility type

5. Detailed Findings

The correlation between and within Areas and Divisions provide more insights about specific VDC practices that significantly affect VDC implementation. Pearson's, Spearman's and Kendall's Correlation tests were conducted to study correlation between and within the VDC Scorecard Areas and Divisions. Smaller p value indicates more significant correlation. Measures that may have contributed to these observations will be discussed in detail, since they give valuable observations about AEC industry practice. It is also possible that some of these critical measures have some causal effect on overall score, and improving on these critical measures could significantly improve VDC performance.

Initial analysis between the VDC Scorecard (Table 5) Area's indicates that VDC Planning, Adoption, Technology applied and Performance are significantly correlated with each other. However, what is of concern is, that VDC Performance, as defined by the VDC Scorecard, showed a low correlations with Planning, Adoption and Technology, opposed to the correlations between, for example Planning and Adoption. This may imply that though, AEC firms are investing on VDC Planning and Technologies, they are yet unable to convert these practices into a definite change in the projects overall performance. These relationships will be discussed in detail in the subsequent sections of this paper.

Table 5: Correlations within the VDC Scorecard Areas: Planning, Adoption, Technology and Performance

Area		Correlation	P-value
Planning vs.	Adoption	0.563	2.35×10^{-10} *
	Technology	0.635	1.58×10^{-13}*
	Performance	0.393	2.54×10^{-15}*
Adoption vs.	Technology	0.574	8.54×10^{-11}*
	Performance	0.361	0.0001*
Technology vs.	Performance	0.306	0.0012*

*Pearson's Correlation coefficient that was significant at 5% significance level. Spearman's and Kendall's statistics gave the same conclusions.

VDC Scorecard → Planning Area:

The only significant correlation within the Planning Area Divisions was between Objectiveness and Standards (Table 6 - only significant correlations at a p-values<0.05, are displayed in all subsequent tables). However, analysis between the Planning Area Divisions and other non-Planning Area Divisions provided insightful correlations (Table 7). As hypothesized by CIFE researchers, results from the 108 cases confirm that Standards did not correlate at all with all the other Divisions apart from the Technology Division – coverage. In contrast, having sound VDC objectives and preparation correlated with most of the other non-Planning Divisions. We observe that the factor VDC objectives correlated only with the quantitative performance, whilst VDC preparation correlated only with qualitative performance. Overall, the Division Objective, had very high correlation values, followed by Preparation and Standard.

Table 6: Correlations within the VDC Scorecard Areas: Planning

Planning Division		Correlation	P-value
Objective vs.	Standard	0.272	0.0040*
	Preparation	0.145	0.1350
Standard vs.	Preparation	0.080	0.4096

Table 7: Significant correlations (p-values<0.05) between the VDC Scorecard Area: Planning and other Area-based Divisions

Planning Division	**Area**	**Non-Planning Area- based Division**	**Correlation**	**P-value**
Objective	Adoption	Process	.467	3.40×10^{-7} *
		Organization	.623	3.32×10^{-13}*
	Technology	Maturity	.498	4.29×10^{-8} *
		Coverage	.433	2.99×10^{-6} *
	Performance	Quantitative	.446	1.32×10^{-6} *

Standard	Technology	Coverage	.205	0.033 *
Preparation	Adoption	Process	.427	4.06×10^{-6} *
		Organization	.321	0.00071 *
	Technology	Maturity	.348	0.00022 *
		Coverage	.291	0.00022 *
		Integration	.474	2.41×10^{-7} *
	Performance	Qualitative	.264	0.005 *

Planning Area: Measure-based analysis

Based on the results obtained further analysis was carried out on the Planning Area measures. Planning Area measures how formalized VDC is to the project team and how well the project team has been prepared for VDC application and management. It includes the measurements toward VDC formalization among project stakeholders, qualitative and quantitative objectives, standards, file management systems and budget. The 108 pilot projects have an average Planning score of 50%, which just achieves the advanced practice category. Table 8 lists the critical measurements under Planning Area, among which establishment of objectives have the most significant correlations to the overall score (P-value < 0.05).

Table 8. Critical measurements under Planning

Area 1 (A1): Planning
Division 1: Objective
1. Stakeholder Formalization
2. Management Objectives
3. Quantifiable Objectives
4. Objective Categories
5. Stakeholder Benefits
Division 2: Standard
1. VDC Guidelines
2. BEP/VDC Guides
3. VDC Development
Division 3: Preparation
1. Project Interaction Mode
2. Project Interaction Coverage
3. Data Sharing
4. VDC Budget
5. VDC Software

Measurement A1>D1>M1(Area 1, Division 1, Measurement 1) of VDC scorecard establishes the assessment towards VDC formalization with the following evaluation levels: 1) personal belief; 2) single company belief; 3) shared belief among companies; 4) documented in one company; and 5) documented and shared with multiple companies. The data indicates that 83% of the project teams have at least shared belief of VDC among multiple project stakeholders, but only 39% of the projects have formalized document and share it within the teams. Most of the AEC industry is aware of VDC being an effective method to improve project performance, but its application has not been fully adopted by all stakeholders. Establishing formalized documentation of VDC objectives is the first step of VDC collaboration and therefore has significant influence toward the integrated performance of project teams later.

Measurement A1>D1>M2 evaluates the number and effectiveness of VDC objectives that the project teams have established. Effective objectives are those that aim at improving facility performance, cost, schedule, safety, project delivery and team-wide communication, and are quantified in order to provide clear standards for the teams to compare the actual project outcomes. The project teams that reported quantitative objectives also achieved higher Performance scores that indicate the level of fulfillment toward initial expectations. The average Performance score for projects with quantitative objectives is 60%, opposed to 39% for projects that do not have their objectives quantified. The top 25% projects in overall performance have 83% of their VDC objectives quantified, while the other projects have only 5% (Table 9). The difference indicates that establishing quantitative objectives contributes significantly to the overall success of the projects.

Table 9. The Planning practice of the top overall 25% projects compares to that of the bottom 25%

Measures	Top 25%	Bottom 25%
Percentage of projects that had documented the VDC planning process and objectives	79%	39%
Percentage of projects that had established quantifiable objectives	83%	5%
Average number of quantitative objectives established	~3	~0

Analysis of other measurements under Planning Area also shows contrast between the typical and advanced practices. Table 10 summarizes the common planning practice patterns and recommendations for improvements:

Table 10. Planning practice patterns and corresponding recommendations for improvement

Common Practice	Recommendation
Stakeholders of the project have shared belief in VDC, but the scope is not formally documented; (44% of the projects do not have formalized VDC documentations.)	Clearly document the scope of VDC application and have it shared among project stakeholders;
Project team has no or few objectives set up; most objectives are qualitative rather than quantitative; (40% of the projects do not have any quantitative objectives.)	Clearly set up VDC related objectives that aim to improve performance in multiple aspects including cost, schedule, quality, safety, communication etc. and quantify the objectives as much as possible; Also set up objectives in regard of the benefits to various stakeholders in order to incentivize the application of VDC;
VDC Guidelines, if any, are set up for particular projects; (39% of the projects had contributed towards program, national or enterprise specific guideline development.)	Develop general VDC guidelines that can also be adopted by future projects;
Project team does not have project management system, or has one that has limited interaction with project data; (5 out of 13 types of project data on average are integrated with project management system.)	Properly select project management system and utilize its integration features.

VDC Scorecard → Adoption Area:

The two Divisions under the Adoption Area, Process and Organization were significantly correlated, as expected (Table 11). It is interesting to note that both these Adoption Divisions were significantly correlated with all the other Divisions, under the VDC Scorecard Areas Planning, Technology and Performance, apart from the Planning Division Standard (as observed in the previous section). The proceeding section describes the specific measurements that may have resulted in these interesting observations with VDC Adoption, amongst AEC projects. Further measurement based analysis showed, that the most critical measure towards the overall VDC Performance (adjusted for the impact of related factors), was the involvement of project stakeholders in VDC projects.

Table 11: Correlations within the VDC Scorecard Areas: Adoption

Planning Division		Correlation	P-value
Process vs.	Organization	.616	1.34×10^{-6} *

Table 12: Significant correlations (p-values<0.05) between the VDC Scorecard Area: Adoption and other Area-based Divisions

Adoption Division	Area	Non-Adoption Area- based Division	Correlation	P-value
Process	Planning	Objective	.467	3.40×10^{-7} *
		Preparation	.427	4.06×10^{-6} *
	Technology	Maturity	.500	3.60×10^{-8} *
		Coverage	.402	1.59×10^{-5} *
		Integration	.389	3.24×10^{-5} *
	Performance	Qualitative	.342	0.0002*
		Quantitative	.253	0.008*
Organization	Planning	Objective	.623	3.32×10^{-13}*
		Preparation	.321	0.00071 *
	Technology	Maturity	.382	4.49×10^{-5} *
		Coverage	.418	6.73×10^{-6} *
		Integration	.199	0.0391*
	Performance	Qualitative	.301	0.001*
		Quantitative	.194	0.043*

Adoption Area: Measure-based analysis

Adoption Area focuses on evaluating the efficiency of organization and the level of collaboration between project stakeholders. Table 13 lists the critical measurements under Adoption. Other measurements include stakeholder's VDC experience level, availability of VDC trainings and promptness in response to RFIs. The average score of the 108 projects in adoption is 51%, which falls into advanced practice. The scorecard results indicate that the owners, architects and general contractors appear to be more supportive toward VDC than the rest of the stakeholders.

Table 13. Critical measurements under Adoption

Area 2 (A2): Adoption
Division 1: Organization
1. Stakeholder Motivation
2. VDC Skill
3. VDC Training Frequency
4. VDC Training Coverage
5. VDC Staff Participation
6. FTE Percentage
7. Stakeholder Involvement
8. VDC Experience
9. Designated BIM Specialist
10. Stakeholder Attitude
11. Stakeholder Action
12. BIM Infusion
Division 2: Process
1. Project Benefit
2. VDC Application
3. Project Delivery
4. Efficiency
5. RFI Response
6. Process Improvement

One of the critical practices that differentiate integrated design from the traditional design-build methods is to have all stakeholders involved early in the project to collaboratively generate design decisions (American Institute of Architects California Council, 2007). Measurement A2>D1>M8 accounts the project phases in which each stakeholder is involved. 65% general contractors and 31% special contractors are involved during the design phases. Projects with advanced overall performance demonstrate higher level of stakeholder involvement than those with typical performance. This indicates the transition from the traditional approach, in which the designs and constructors are separated in time and responsibilities, to the integrated design approach. The combined expertise from designers and contractors substantially helps synchronize design and construction, from which 81% of the pilot projects reported benefits. Unexpected changes can be avoided by evaluating the design decision more comprehensively in the earlier stage. However, the level of constructor's engagement needs to be further improved in order to leverage the industry's VDC practice.

BIM-integrated project meetings are also shown to be critical to project success. Measurement A2>D2>M4 evaluates the frequency and effectiveness of BIM integrated project meeting with the following performance levels: 1) integrated meetings not held; 2) Weekly meeting with BIM consultants; 3) Model used to identify challenges and come up with solutions, and 4) ICE and lean methodology that involve multiple stakeholders. 95% of the top scored projects use BIM models among multiple stakeholders to resolve engineering challenges (Table 8.). The BIM integrated meetings and engineering sessions encourage communication and allow direct interaction between disciplines, during which open issues can be solved quickly (Chachere, J., Kunz. J, & Levitt, R., 2004).

Table 14. The Adoption practice of the top overall 25% projects compared to that of the bottom 25%

Measures	Top 25%	Bottom 25%
Percentage of Stakeholders Involved	84%	35%
Stakeholders attitude towards VDC	100% of the stakeholders were supportive or more positive towards VDC	54% of the stakeholders were supportive or more positive towards VDC
Average number of phases covered by stakeholders	5.2	4
Efficiency of VDC/BIM integrated Project-Wide Meeting	100% had Integrated Project-Wide Meetings	33% had Integrated Project-Wide Meetings

There's large margin for improvements in Adoption Area based on the comparison between best and worst performing projects (Table 14), as summarized in Table 15.

Table 15. Typical adoption practice patterns and corresponding recommendations for improvement

Common Practice	Recommendation
Decisions are mostly made by one or very few stakeholders that are specified in the particular field; (On average 75% of the stakeholders are involved in VDC, and on average in 4 of the 7 construction phases)	Engage more stakeholders in the project as early as possible and actively support the decision-making processes. For example, special contractors should make input during the design phase to assist designing pre-fabricated elements;
Stakeholders start to get involved in the phase where they are contractually required to perform the major work; (65% of general contractors and 31% of special contractors are involved during design phases.)	
Some stakeholders are supportive toward VDC, and others are unsure or resistant because of the extra cost and effort required for operation; (83% of the stakeholders were supportive towards VDC)	The project team should refer to objective setting in Planning Area, ensuring that the application of VDC will bring benefits to all stakeholders, which will potential become their motivation;
Many project teams do not measure the efficiency of their BIM meetings, and the meetings are held infrequently; (17% of the projects did not hold any meetings)	Set up frequent schedules and agendas for BIM meetings and track efficiency such as number of issues being solved. Also explore more innovative communication and facilitation methods such as integrated concurrent engineering (ICE) sessions.

In addition, CIFE researchers recommend project teams to provide training to the stakeholders who are inexperienced with VDC. The experienced stakeholders should drive the effort of VDC application and motivate others by providing assistance when needed. They should also be the major coordinators of BIM meetings and engineering sessions. Inexperienced stakeholders should value the project as an opportunity to raise their competency toward VDC and be supportive to its application. They should attend trainings if offered and participate in the project as early as they can.

VDC Scorecard → Technology Area:

All three Technology Divisions were correlated with each other (Table 16). There is a very high correlation between Coverage and Integration of Technology, opposed to for example the correlation between Maturity of the Technologies and their Coverage. Technology Divisions Maturity and Coverage correlated with the Quantitative Performance measures and not with the Qualitative Performance measure. In contrast Technological Integration correlated highly with the Qualitative Performance measure, opposed to the Quantitative Performance measure. Similar to the observations made in the Adoption Area, Technology based Divisions did not correlated with the Planning Division Standard (Table 17), but did correlate with other Divisions.

Table 16: Significant correlations (p-values<0.05) *within the VDC Scorecard Areas: Technology*

Technology **Division**		Correlation	P-value
Maturity vs.	Coverage	.326	0.0005
	Integration	.280	0.003
Coverage vs.	Integration	0.455	1.38×10^{-6} *

Table 17: Significant correlations (p-values<0.05) *between the VDC Scorecard Area: Technology and other Area-based Divisions*

Technology Division	**Area**	**Non- Technology Area- based Division**	**Correlation**	**P-value**
Maturity	Planning	Objective	.498	4.29×10^{-8} *
		Preparation	.348	0.00022 *
	Adoption	Process	.500	3.60×10^{-8} *
		Organization	.382	4.49×10^{-5} *
	Performance	Quantitative	.258	0.007
Coverage	Planning	Objective	.433	2.99×10^{-6} *
		Preparation	.291	0.00022 *
	Adoption	Process	.402	1.59×10^{-5} *
		Organization	.418	6.73×10^{-6} *
	Performance	Quantitative	.267	0.005
Integration	Planning	Preparation	.474	2.41×10^{-7} *
	Adoption	Process	.389	3.24×10^{-5} *
		Organization	.199	0.0391*
	Performance	Qualitative	.226	0.018

Technology Area: Measure-based analysis

With the rapid development of BIM related computer modeling software, project teams nowadays are being exposed to a large pool of software choices to aid their analysis, design and construction. The application of software involves the consideration of the appropriateness of software to the project purpose, the level of detail that is required for certain phases, as well as the interoperability of the software in regarding to the model sharing system. These considerations form the major measurements in the Technology Area of the scorecard. The 108 pilot projects received an average technology score of 50%, which has just achieved advanced practice.

Table 18. Critical measurements under Technology

Area 3 (A3): Technology
Division 1: Maturity
1. Level of Application
Division 2: Coverage
1. 3D Elements
2. LoD Support
Division 3: Integration
1. Model Exchange Format
2. Interoperability
3. Average LoD
4. LoD Adequacy
5. Software Adequacy
6. Hardware Adequacy
7. Business Loss Impact
8. Stakeholder Application
9. Member Application
10. Customer Communication

Use of models in the five defined Levels of Development (LoD) is found to correlate significantly to project success (AIA, 2012). The number of recommended software being used at each level establishes the measurement of model use maturity. Software that is recommended at each level by the CIFE research team per defined in AIA E202 document is listed in Table 19.

Table 19. Recommended software use at each level of development(LoD)

Level	Model Uses
1. Visualization **Models are created for visualization purposes (Analysis not required)**	Mass model study, 3D rendering, 4D animation, Organizational chart, Scheduling for presentation
2. Documentation **Models are created for documentation with accuracy up to construction tolerance**	Design/construction documents, Product/ system specification, 3D laser scanning for existing condition, Quantity takeoff, RFI, Punchlist
3. Model-Based Analysis **Models are created to support discipline-specific analysis**	Spatial validation, Structural analyses, Energy analyses, Thermal comfort, Daylight and interior lighting analyses, Fire & smoke, Life safety/egress, Cost estimating, Acoustics, Security Analyses, GIS, Computational fluid dynamic simulations, Construction safety
4. Integrated Analysis **Models/analyses of multiple stakeholders are interoperated for cross-discipline collaboration**	Clash detection, Integrated 4D/5D models, Change order management, Supply Chain Management - RFID, color coded tracking, Facility management
5. Automation & Optimization **Routine analyses or fabrications are automated**	Off-site fabrication, Automation of analysis (code check)

CIFE researchers found that more than half of the overall top 25% projects have used models in all five levels, and more than one software at each level have been used to assist design.

Model use and level of development are also determined by the level of information required at each phase of the project. The model elements should be complete enough to allow critical decision-making at a certain phase and to prepare for progress in the next phase. However, more detailed models than required are not recommended to avoid spending extra time to modify if changes occur in the future. The CIFE research provides a recommendation for LoD to be used at project phase in Table 20 where the darker checks mean recommended and the lighter ones mean acceptable.

Table 20. Recommended LoD at each project phase.

	Pre-Design	Schematic Design	Design Development	Construction Documentation	Construction	Closeout	O&M
Conceptual	✔						
Approximate Geometry	✔	✔					
Precise Geometry		✔	✔				
Fabrication			✔	✔	✔	✔	✔
As-Built				✔	✔	✔	✔

Interoperability of models is another critical measurement toward VDC (Kam, et al., 2003, 2004). Information loss during model exchanges has been reported as problematic by many project teams. Only a few project teams of the top overall 25% were able to keep their information loss minimal (mostly less than 10% - Table 21).

Table 21. The Technology practice of the top overall 25% projects compares to that of the rest in information loss during model exchanges.

Feature	Top 25%	Bottom 25%
Average percentage of product elements modeled in 3D	76%	39%
Projects with less than 5% of Interoperability Information Loss	37%	7%

Based on the findings of typical practice regarding technology use, CIFE researchers provide the following recommendations regarding technology application:

Table 22. Typical Technology practice patterns and corresponding recommendations for improvement

Common Practice	Recommendation
Project teams do not have a planned schedule for model uses at each project phases. Most details in the model are made based on immediate requests;	Refer to Table 20 above and plan to achieve proper LoD for each project phases that allows enough information for all stakeholders to complete their work.
The maturity of model uses is moderate with two or three LoD being modeled and limited number of software being used; (53% of the project teams used software under the level of Automation & Optimization)	Refer to Table 20 above and the plan for model LoD usage at each phase, choose proper software to assist design and construction;
Information loss during model exchanges causes inaccuracy and takes time to recover; (77% had an Interoperability Information Loss of more than 5%)	Research on the features of software and coordinate with the whole project team to select modeling software that has high interoperability. Also create model operational guidelines including uniform file format, naming structures, modeling coordinates, scales etc.

Young VDC and BIM project teams should engage experienced VDC experts or consultants to assist modeling and training. As they become more sophisticated, the project teams should refer to the tables above to develop high quality information models and explore other innovative methods to eliminate error and information loss during model exchange.

VDC Scorecard → Performance Area:

Though statistically significant at 5% level of significance, the correlation between VDC Performance measured considering Quantitative and Qualitative measures is not very high (Table 23). It is further interesting to note that these two measures, unlike the patterns observed so far, within the Planning, Adoption and Technology Areas, show contrasting correlation patterns with other Divisions (Table 24).

Table 23: Correlations within the VDC Scorecard Areas: Performance

Performance Division		Correlation	P-value
Quantitative vs.	Qualitative	.202	0.035

Table 24: Significant correlations (p-values<0.05) *between the VDC Scorecard Area: Performance and other Area-based Divisions*

Performance Division	**Area**	**Non- Performance Area- based Division**	**Correlation**	**P-value**
Qualitative	Planning	Preparation	.264	0.005 *
	Adoption	Process	.342	0.0002*
		Organization	.301	0.001*
	Technology	Integration	.226	0.018
Quantitative	Planning	Objective	.446	1.32×10^{-6} *
	Adoption	Process	.253	0.008*
		Organization	.194	0.043*
	Technology	Maturity	.258	0.007
		Coverage	.267	0.005

Performance Area: Measure-based analysis

Performance Area focuses on measuring the outcomes of VDC planning, adoption and technology application against the original project objectives. It also includes the measurement toward the frequency of performance tracking and the VDC users' emotions. The average performance score of the pilot projects is 47%, which is categorized as typical practice. Performance Area received the lowest average score with largest dispersion among the four Areas of the scorecard, and it was harder to identify a typical practice pattern of performance from the scoring results. One reason is that only a few project teams have tracked their actual performance and compared the outcomes to the initial objectives; 60% of the pilot projects, as described in the Planning Area, did not set quantitative objectives at the beginning and therefore have no targets to which the actual outcomes can be compared. The outcomes could only be measured according to the subjective opinion of project teams. Few projects achieved preferable results only as 'surprises' for which they did not set initial objectives. The lack of comparison data between objectives and actual performance indicates that the industry's application of VDC is rather commonly in an ad-hoc fashion rather than systematic. The AEC project teams have limited control over the outcomes resulted from their design and construction activities.

Table 25. Critical measurements under Performance

Area 4 (A4): Performance
Division 1: Quantitative
1. Objective Tracking
2. Performance Measurement
3. Planning & Mode ling Alignment
4. RFI Expectation
5. Unforeseen Order Change
6. Field-Initiated Order Change
7. Target Achievement
8. Target Maturity
Division 2: Qualitative
4. 1 Performance Assessment
4. 2 Model Assessment
4. 3 Satisfaction & Importance
4. 4 User Satisfaction

Despite less data was received regarding performance, the analysis result from existing data demonstrates that constantly tracking performance and adjusting activities to fulfill the planning targets contributes to successful project delivery. 86% of the top scoring projects reported fulfillment of their quantitative targets (Table 26).

Table 26. The Performance practice of the top overall 25% projects compares to that of the bottom 25% in fulfilling quantitative and qualitative objectives.

Measures	Top 25%	Bottom 25%
Satisfaction with Qualitative Objective	88%	66%
Satisfaction with Quantitative Objective	86%	25%
Overall user "Emotions" with regard to VDC	100% of the project stakeholders showed a sense of satisfaction or more positive emptions	77% of the project stakeholders showed a sense of satisfaction or more positive emptions

Another critical measurement under performance is the VDC users' emotions. A successful delivery of project using VDC will enrich its stakeholders experience and raise their confidence toward future projects. It is found that all the overall top 25% project are satisfied with VDC and some have expressed gratitude and feeling of growing competency. Table 27 indicates the common practice regarding performance and recommendations from the CIFE researchers:

Table 27. Common performance practice patterns and corresponding recommendations for improvement

Common Practice	Recommendation
Performance is rarely tracked and compared against initial objectives, or outcomes are only reviewed at the end of the project; (6% of the Quantifiable Objectives were tracked)	Project teams should set up targets for all performance categories at the planning stage (see recommendation in planning). These targets can be broken down into milestones. Constantly track and report performance, and readjust activities if necessary. Feedback on performance can be presented during project team meetings (see recommendation in adoption) or constantly updated in the project management system (see recommendation in planning);
Measurements toward target achievement are subjective and therefore can be inaccurate;	Set up quantifiable objectives (see recommendation in planning). Review performance and outcomes weekly or more often;

7. Case Studies

Two case studies of the pilot projects are presented in addition to the summary results by Areas to demonstrate the detailed VDC practices related to the scorecard measurements. The individual case studies also indicate how VDC affects the project overall outcomes in both positive and negative ways through cross comparison between the performance of example cases and the average of all pilot projects. The following two case studies both demonstrate advanced VDC strategies that lead to desired outcomes as well as the potential for improvements.

Case I: Healthcare project in California

Project Profile:

Facility	**New Healthcare**
Project Size	> 200,000 square feet
Location	California
Construction Budget	> $300 million
Starting Date	2007
Current Phase	Closeout
Delivery Method	IFOA/PPP
Stakeholders Involved	owner, end user, architect, engineer, VDC consultant, general contractor, special contractor and regulatory agency

Case I has been evaluated three times using the VDC scorecard. In the most recent evaluation, it received an overall score of 79%, which is categorized into best practice, with a confidence level of 65%. It is one of the most innovative projects among the 108 have been evaluated.

Best Practice: The team collaborated in a highly integrated manner throughout the entire project under an IPD contract. The input under Adoption Area indicates that the collaboration between the owner, end user, designers, general contractor and the VDC consultant started from the pre-design phase and was kept throughout the entire project. The team also brought in OSHPD at the beginning of the project in order to accelerate the approval process, while the scorecard general finding indicates that only 8% of the regulatory agency expressed supportive attitude toward participating in VDC during project design and construction. In traditional design and construction approach, the designers and contractors are usually separated in responsibility and time of involvement. However on this project, the special contractors were involved previous to construction to consult design for prefabrication.

Compared to the typical performance where VDC is rather utilized when trying to achieve certain desired outcomes instead of formally documented as a project management procedure, this project team established management plans that include aggressive objectives in order to push the project to a better outcome, among which six are explicitly quantified:

Objectives	Actual Performance
Less than 300 **RFIs project wide**	
100% **cost conformance ($320 million)**	9% of actual cost
Less than 100 **OSHPD change orders**	
Accelerate **OSHPD structural permission process to** 15 **months**	Expedite structural permitting procedure of 15 months relative to comparable OSHPD project of 39 months
Less than 2 **days response latency**	Design and construct 30% faster than the past comparable projects in California
14% better **energy performance than Title 24**	

While 88% of the scored projects review their performance outcomes monthly, quarterly, annually or once at the end of their projects, this project team was tracking their performance against initial objectives continuously throughout the entire project, and reported notable improvements as indicated by the scorecard evaluation results (Figure 4). The project team especially highlighted the achievements of desired outcomes correspond to the quantitative objectives listed above and indicated that 3 of the actual outcomes have exceeded their expectations. The saved cost (about $14,000) will be shared among stakeholders as profit.

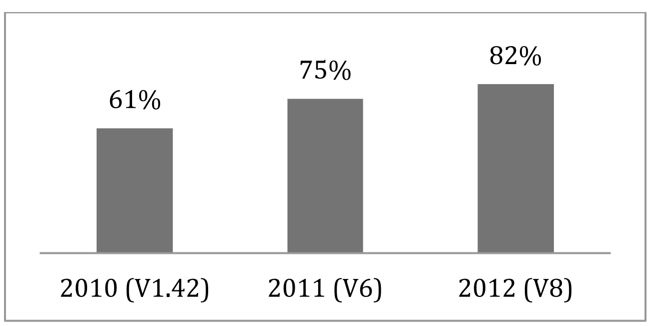

Figure 4. Improvement in performance indicated by the VDC scorecard results

This project received the highest adoption score of 92% among the 108 pilot projects. The owner, general contractor and VDC consultant of Case I are experienced VDC users and have been driving the collaboration efforts. VDC training was offered to the other stakeholders upon request. Co-located BIM meeting was held in Big Room every two weeks for 3 days for the entire team to review design, schedule, workflow and budget.

The project team has used 24 applications in total that cover all five maturity levels in the Technology Area. The contractor's estimating team set up an automated estimating process to generate cost estimates more easily and frequently. The mechanical and plumbing teams worked closely together to create models using the same application and took another step toward off-site fabrication and pre-assembly. It was also innovative for the project team to reach out the software vendor, TSI, to resolve software limitations during the process of advancing models through the steps of design–fabrication–assembly. (This paragraph was taken from the SMCCV report done by previous CEE 212 student) The team created as-built BIM model for construction, and was able to prefabricate many elements off site, include steel sections, all MEP ducts and pipes and stairs, to name a few. The project team expressed gratitude toward the application of VDC. The team was able to successfully delivery the project with the initial objectives achieved.

Case II: Cultural/Entertainment project in Europe

Project Profile:

Facility	**New museum**
Location	Europe
Construction Budget	$127 million
Starting Date	Construction started in 2008
Current Phase	Construction
Stakeholders Involved	owner, architect, engineer, VDC consultant, general contractor and special contractor

Case II is a $127 million museum project located in Europe. The project team is consisted of ten firms located worldwide with over 400 individuals, including the owner, architect, engineer, VDC consultant, general contractor and special contractor. This project is unique in the way that the museum architecture itself is highlighted as part of the indicator of modern art and culture. Besides, the building has a highly complex geometry and intensive use of glass with curved surfaces. The project member expressed during the interview that these factors posted many challenges to the project team that have rarely been faced before.

Software Application for Case II: DigitalProject, Tekla, Sketchup, AutoCAD, BoCAD, SolidWorks, ANSYS, STRAUSS, NASTRAN, Sofistik, 3DVia Composer, Solibri

The project is currently under construction, and has been evaluated one time by the VDC scorecard in earlier 2012. The project received 66% as overall score with a confidence level of 23%, which brings it to the advanced practice category. This project was presented with the AIA 2012 BIM Excellence Award with an outstanding performance in technology application.

Best Performance: From the beginning of the project, the team had a common ambition of deliver a contemporary building with the most innovative material and system that is built in harmony with the historical culture and environment of the site by using today's cutting edge technology. This general objective became the firm motivation of applying VDC to the project. The project team reported formally documented VDC scope that is shared with all stakeholders under the scorecard Planning Area. The general ambition also originated the detailed objectives that dedicated to the improvement of communication, facility performance, safety and project quality. These objectives include but are not limited to perform concurrent modeling and data maintenance; pursue prefabrication through CNC molded concrete and glass panels; and reduce uncertainty during construction by verifying the shape and dimension of components before shipping; and provide as-built model for facility management. Distinguished from the traditional structured AEC teams, this project has a separated consulting team dedicated to the adoption of digital process. It provided training and tutorial on digital software to the design divisions, and developed innovative tools that were specially customized for this project. These performance attributes have

The most advanced VDC practice of this project is under Technology Area for which the project received 74%. The highlight falls on its technology application that has demonstrated an evolution toward multidisciplinary collaboration using cloud approach. The cloud model management system server allowed the usage of design, analysis and construction software, and storage a master BIM model that integrates comprehensive design and consulting information.

The software application covers all five levels of technology maturity, including visualization, documentation, model-based analysis, integrated analysis and optimization, throughout all phases during the project. The server had nearly 100 gigs of BIM model data due to complexity of the building. The project team was able to develop efficient strategies to organize and manage this vast amount of data: the model structure and file organization comply with organization chart. All the discipline specific models are linked to the master architectural model, and to which changes were tracked by cloud versioning tools. The project team also defined three levels of modeling details that are dedicated to different phases:

- PRO: The design team's authoritative document;
- INT: The contractor's real-time, working model;
- EXE: The high-fidelity synthesis of the two, used for construction.

The finished BIM model contains not only the as built information of each building elements, but also the material life cycle and future projected behaviors that will be used to provide maintenance routine after the museum is open to the public. This level of building information was enabled through the input of consultants and subcontractors who were early engaged in the design process.

The project team emphasized another advanced VDC practice under Technology Area of using BIM model to enable material optimization, automated fabrication and quality control of the façade glass panels. The BIM model was first analyzed to find best-fit cylinders of glass panels on the highly irregular façade. Further analysis was performed to adjust geometry to reduce variation. By identifying the shape and frequency of these panels, the team was able to industrialize the fabrication by using a CNC bending machine. The produced panels were scanned and positioned back into the model to confirm correct design and fabrication before shipped to the site. This integrated process substantially helped in reducing material use, accelerating schedule and minimizing risks, all of which could not be achieved otherwise by using traditional design and construction process.

8. Successes and Shortcomings of the use of VDC

Successes: 86% of project teams expressed contentment and gratitude toward the value added to their projects by applying VDC. These values are received through the form of cost saving, shortening construction duration, enabling more efficient and sustainable design, better collaboration experience and project delivery. VDC enabled visualization allows designer and contractors to detect and fix issues prior to the start of construction that would otherwise cause rework. VDC has also gained favor among owners and end users to whom it's hard to provide design input without being able to visualize project details, and therefore are typically not involved in the traditional design and construction process. With VDC, they are able to 'experience' their buildings and provide more specific requests to the design teams. At the end they are more likely to receive a building product that functions as desired. On the enterprise level, the value added by VDC becomes the designers and contractors' competency and reputation of being able to perform integrated design and construction. Among the vast benefits that the teams of the 108 projects received, some examples are presented:

- *"The implementation of a highly collaborative BIM process allowed us to create an award winning LEED Platinum project on budget, ahead of schedule, with minimal RFI's and no change orders"* (HOK BIM Awards - Project, 2011)
- *"Our user group meetings have been productive and with all of the 3D views the model has really shown the client that we know exactly what they want and that we will be able to do it for them. We have actually received the comment from the client that "all we do is blink and out designers have drawn it up for us"* (HOK BIM Awards - Project, 2011)
- *"Of hundreds of clashes, the team conducted a cost study based on 16 clashes within these categories that were identified as issues that would have been undetected in a traditional design process, and consequently, unresolved prior to onsite installation and construction. These 16 clashes resulted in an estimated cost saving of close to $1.3 Million in problems the team was able to resolve prior to the initiation of construction"* (AIA TAP BIM Awards - Project, 2012)
- *"To design for 23 acres of landscaping, the project team has evaluated over 60 plant types. Each plant type may flourish or suffer depending on their solar access, which includes many variables such as the species, the orientation, shade from building/terrace. Rather than doing spot design, BIM allowed us to objectively predict annual solar exposure of each terrace, and calibrate the results with the plant species characteristics"* (AIA TAP BIM Awards - Project, 2011)

Shortcomings: However, project teams that use VDC in the AEC industry have opportunities to improve its current benefits from VDC. Less than 40% of the 108 projects scorecard using the VDC Scorecard, tracked and monitored quantifiable metrics despite the clear benefits of tracking and monitoring metrics that are key performance indicators. In other industries, methodologies that use metrics and analyze a project's status and provide feedback are both available and effective (Zevenbergen, 2006). In addition industries, such as manufacturing and information technology, use metrics more systematically and successfully. Esin et al's (2009) study on the usage of metrics in the apparel industry pointed out that 80% had some form of quantifiable metrics tracked and monitored. The systematic monitoring of VDC via quantifiable metrics is currently a major shortcoming. Other shortcomings include, that only 57% of the 108 cases had documented VDC planning and process-related objectives, only 41% of the 108 cases had allocated more than 1% of the projects budget towards VDC related tasks, and only 27% of the projects had an interoperability information loss of less than 5%..

9. **Validation**

The results of this study use a comprehensive collection of 108 unique VDC projects. Also, the correlation results in this paper are validated using the statistical technique of bootstrapping (Efron and Tibshirani, 1993), which is commonly used for small datasets. These results did not change.

It was further required to validate the VDC Scorecard methodology, as a suitable framework to provide reliable and generalizable results. The aim of the VDC Scorecard is to provide, a holistic, quantifiable, scalable and practical tool to monitor and evaluate the use of VDC, amongst AEC firms. CIFE research provides holistic findings related to both social collaboration and on capturing the performances of the creation and implementing the product model of a project. These, findings include those related to stakeholder involvement, the effectiveness of integrated meetings, the appropriateness of models used, and the overall satisfaction with VDC, to name a few. The performance of project objectives are quantifiably measured based on communication, cost performance, schedule performance, facility performance, safety, project quality, and other objectives established based on project needs. The VDC Scorecard is designed to adapt to changing VDC industry practices as well as industry trends. The VDC scorecard is under constant update and development to be a valid and comprehensive tool for the AEC professionals to evaluate project performance. The scoring weight of individual practice will be readjusted once the CIFE researchers find solid evidence that demonstrates the change of its maturity level. The CIFE researchers validated the VDC scorecard results through conducting a series of statistical analysis to calculate score averages and identify trends and correlations. The average VDC overall score of 108 pilot projects is 50%, which is the middle point on a 0% to 100% scale. It indicates that the scoring weight assigned to each measurement well represents the influence of the measurement toward overall VDC performance. The VDC Scorecard is practical in that the express version can be completed within half an hour, yet with a low confidence score, and has the capacity to provide quick quantitative feedback (Kam, McKinney, Xiao, Senaratna, 2013). Further, it is realistic since the VDC Scorecard has a concept namely a “Confidence Level,” which quantifies the accuracy of the VDC Scorecard based on the quality of responses obtained.

10. Future Work

While the findings of the VDC Scorecard represent the characteristics of the current design and construction practices of the AEC industry, they are also subjected to limitations that have been identified by the CIFE researchers and will be improved and eliminated in the future. The scorecard input emphasizes more on the VDC performance during design and construction. The number of projects being evaluated is limited to 108, and the data is dedicated unevenly to facility types, locations and other project features. As a solution to better generalize the findings, CIFE researchers will weight findings based on nation-wide features as well as analyze the data considering similar project-types. The findings and confidence level will be further refined through evaluation of projects with larger number and variety in facility types, project phases, locations, contract types, and delivery methods, etc.

Most project results (except for 15 projects that have been evaluated by the VDC Scorecard multiple times) are also limited to one time evaluation, and therefore are subjected to the amount and accuracy of information that the project teams could provide at the time of the interviews. The score results of projects in early phases such as pre-design and schematic design involve a certain level of projection and assessment toward performance tracking and project outcomes. Each project will be rescored under design and construction phases in the future to examine the progress in collaboration and improvement of results. The VDC Scorecard is also continuously being updated and developed in order to best represent the current AEC industry's practice.

The VDC Scorecard still places significant importance in the quality of Planning, Adoption and Technology Areas because we anticipate the process of VDC application to contribute to the final Performance of projects. Thus, the VDC Scorecard can provide actionable recommendations on the process of AEC projects that will result in better final performance. However, the correlation between each of the three other Areas against Performance Area was lower than expected, and R^2 does not exceed 0.4 between each of the three Areas and Performance Area. In most instances a low correlated is attributed to shortcomings in the industry, and not issues with the Scorecard. However, researchers use statistical findings on correlation patterns between individual measures, together with industry knowledge to refine the Scorecard.

Research studies in management science have emphasized the value of objective performance tracking. Many industries such as manufacturing and information technology use objective metrics to systematically and successfully improve performance (Esin et. al, 2009 and Zevenbergen, 2006). Similar to the green building industry, the VDC Scorecard will not only enrich the knowledge of AEC professionals, allowing an accurate assessment of the market, performances, challenges, and trends, but the VDC-related knowledge repository will also bring opportunities for new research and constructive criticism that can be based on a solid and well-substantiated database. This will create a healthy feedback loop among academia, organizations, and the industry, and will ultimately help practitioners to optimize VDC on their projects and maximize returns. These returns include, better building performance, lower costs, faster schedules, improved communication, and improved worker safety.

Conclusion:

The VDC scorecard results from the 108 projects across 13 countries provided evidence to identify critical practice factors that have major influences on the project teams' overall integrated performance. These practice factors include formalization of VDC among stakeholders: number and effectiveness of VDC management objectives; stakeholders' attitudes toward VDC; percentage and duration of stakeholder involvement; use of technology applications; and the level of achievement. The analysis of these results also helped in identifying the average maturity level and common practices of VDC within the AEC industry. It is stated by the pilot project teams that VDC has brought benefits to their projects in many different aspects, such as cost saving, duration shortening, as well as improved project quality and communication. Through the past and ongoing project input, the CIFE researchers will constantly update the VDC scorecard and identify potential of VDC to be further developed to assist the AEC industry in better achievement of its business objectives. This effort calls for a higher level of participation of the AEC profession to create more detailed and better-shaped action plan for operation.

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