



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE  
SCHOOL OF ENGINEERING

# **A METHOD TO IDENTIFY VIRTUAL DESIGN AND CONSTRUCTION IMPLEMENTATION STRATEGIES FROM A LEAN CONSTRUCTION PERSPECTIVE**

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Thesis submitted to the Office of Graduate Studies in partial fulfillment  
of the requirements for the Degree of Doctor in Engineering Science.

Advisor:

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Santiago de Chile, November, 2016

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This thesis is dedicated to my parents,  
my sister, and my grandparents  
for their love, endless support,  
and encouragement.

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## RESUMEN

Existen importantes avances en las sinergias entre el modelado de información de construcción (BIM), como parte del diseño y construcción virtual (VDC), y la construcción lean. Sin embargo, la literatura no explora completamente la naturaleza o razones conceptuales detrás de estas sinergias. Una mejor comprensión de estas sinergias permitiría a la industria de la arquitectura, la ingeniería y la construcción (AEC) lograr una mejor implementación entre lean y VDC, y sería un peldaño para seguir diseñando nuevas sinergias.

Además, en los últimos años, la industria AEC ha ampliado el uso de VDC; especialmente los métodos de construcción lean, para ofrecer un mayor valor a sus clientes. VDC incluye el uso de la gestión de producción utilizando métodos lean como parte integral de su método y teoría. Múltiples casos de estudio han concluido que se logran mejores resultados mediante la implementación de ambas iniciativas en conjunto.

A pesar de la gran importancia de ambas metodologías, VDC sigue siendo un desafío ya que las empresas carecen de estrategias de implementación y su relación con la construcción Lean.

El objetivo de esta investigación es diseñar una metodología sistemática que permita a las empresas AEC identificar las mejores estrategias de implementación de los modelos VDC y su impacto en el desempeño con la construcción lean como moderador.

Para alcanzar el objetivo final se llevaron a cabo los siguientes objetivos específicos:

- Se llevó a cabo **una revisión de la literatura** para explorar las sinergias entre la construcción lean y VDC, incluyendo BIM (producto), modelado de procesos y organización;
- Se creó un **modelo de interacciones** entre los elementos de VDC, incluyendo moderadores en relaciones específicas;
- Se analizó la frecuencia de las referencias en la literatura utilizando un método estadístico (cuadrados mínimos parciales de PLS) para probar **las hipótesis nulas** y evaluar el significado de las relaciones y los moderadores.

- **Se informaron y discutieron los resultados.**
- **Se dibujaron las conclusiones en base a los resultados.**

Este estudio tiene contribuciones académicas y prácticas. La principal contribución teórica al conocimiento en el campo de VDC y Lean es el diseño del modelo de influencia VDC/Lean, basado en evidencia estadísticamente significativa entre las relaciones de los elementos en la implementaciones de VDC con Lean como moderador. Los resultados indican que se alcanzan mejores resultados del proyecto cuando Lean es un elemento integral dentro de la implementación de VDC.

Una contribución práctica es que los profesionales pueden usar las ideas y los hallazgos para apoyar las decisiones sobre la implementación de VDC y Lean dentro de la industria AEC.

Como se mencionó, los modelos de VDC se implementan de acuerdo con anécdotas y creencias basadas en proyectos pasados, que han motivado a muchos proyectos y empresas en muchos países a usar métodos VDC, pero aún no han llevado a la adopción universal en todo el mundo.

## ABSTRACT

There have been important advances regarding the synergies between building information modeling (BIM), as part of virtual design and construction (VDC), and lean construction. However, the literature does not fully explore the nature of or conceptual reasons behind these synergies. A better understanding of these synergies would allow the architecture, engineering and construction (AEC) industry to achieve better lean and VDC implementation, and would provide a stepping-stone for academia to continue building on these synergies.

Furthermore, in recent years, the AEC industry has broadly expanded the use of VDC; particularly lean construction methods, to deliver value to their customers. VDC includes the use of Production Management using lean methods as an integral part of the defining theory and method, and multiple case studies have concluded that the projects with the best performance use both initiatives together.

Despite the great importance of both methodologies, VDC remains a challenge as companies lack understanding of the implementation strategies and their relation with Lean management.

The objective of this research is to design a systematic methodology that enables AEC companies to identify the best VDC implementation strategies and its impact on performance with lean construction as a moderator.

My research method included the following steps:

To achieve the final objective of this study some specific objectives had to be carried out:

- **Conduct literature review** to explore the synergies between lean construction and VDC, including BIM (product), process and organization modeling.
- **Create model of interactions** between elements of VDC, including moderators of specific relationships;

- **Frame the null hypothesis that, considering frequency of references in the literature,** interactions in the model are not statistically significant.
- **Analyze frequency** of references in the literature using a statistical method (partial least squares of PLS) to test the null hypotheses and assess significance of relationships and moderators.
- **Report and discuss findings**
- **Draw conclusions based on findings.**

This study has academic and practical contributions. The main theoretical contribution to knowledge in the field of VDC and Lean is the design of the VDC/Lean influence model, based on statistically significant evidence of relationships between elements of VDC implementations with Lean as a moderator and evidence that the best project outcomes are found when Lean is an integral element of the VDC application. A potential practical implication is that practitioners can use the insights and findings to support decisions on the implementation of VDC and Lean within the AEC industry.

As we mentioned, VDC models are implemented according to anecdotes and beliefs based on past projects, which have motivated many projects and companies in many countries to use VDC methods, but they have not yet led to universal adoption around the global.

## 1 BACKGROUND

Several important challenges facing the Architecture, Engineering, and Construction (AEC) industry motivate practitioners to adopt new methods, such as Virtual Design and Construction (VDC) models (Fischer and Kunz, 2004). The VDC approach changes how we design, build, operate, and maintain buildings and infrastructure as a whole (Gao, 2011), and the use of VDC models has expanded considerably (Dave et al., 2013; Hardin and McCool, 2015; Kong, 2010; Mandujano et al., 2016; O’Ryan, 2011; Volk et al., 2014).

Kunz and Fischer (2011) define VDC as *“the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives.”* The VDC approach mainly aims to model the complexity in construction projects and thereby help managers understand the potential difficulties between project team members, analyze risk, and work out solutions in a virtual world before performing any construction work in the real world (Khanzode et al., 2006).

An increased demand for profitable projects that meet deadlines has led to new processes in project delivery, with many based on VDC models used to automate or integrate tasks (Morgan and Liker, 2006). New ways of working within the AEC industry has been a major issue in the drive to improve construction project efficiency for the duration of their life cycles and across different business functions (O’Ryan, 2011). The key element of success is to accept the change as a new way of working within a traditional and fragmented industry (Blayse and Manley, 2004). Businesses are moving from traditional to modern, efficient processes mainly through VDC. A study by the Center for Integrated Facility Engineering (CIFE) of Stanford University indicates that users find great value in the VDC models and their use is growing in both the number of users and the intensity of their application. As intensity of VDC use increases and users become more efficient, they perceive greater value and choose to change both organizational and strategic operations (Gilligan and Kunz, 2007).

On the other hand, lean construction, as defined by the Lean Construction Institute (LCI), is a production management-based project delivery system emphasizing the reliable and

speedy delivery of value. The goal is to build a project while maximizing value, minimizing waste, and pursuing perfection for the benefit of all project stakeholders. The literature indicates hundreds of interactions between these two approaches (Sacks et al., 2010) and suggest that stakeholders' goals are more likely to be fulfilled when these approaches are carried out together (Alarcon et al., 2013; Arayici, Kiviniemi, et al., 2011).

VDC is a new method that will help the AEC industry achieve Lean Principles by eliminating waste, improving value and productivity, reducing costs, and creating positive results within a project, with a common goal of improving the construction and design process (Eastman et al., 2011).

Currently, there are no methods to identify the best strategies for implementing VDC to improve project and firm performance (Fischer and Kunz, 2004; Gao, 2011; Gao and Fischer, 2008; Kong, 2010; O'Ryan, 2011). The impact of these strategies on implementation processes and their interaction with lean is also unknown.

In order to close this gap, this research aims to develop a performance modeling methodology that will allow architecture, engineering, and construction (AEC) companies to design virtual, design and construction (VDC) implementation strategies, including lean management as moderator.

Conceptual definitions and scope of VDC and BIM, evidence that VDC allows for more interactions with lean than BIM, new interactions between Lean Principle and VDC/BIM, identified waste and improvement methods in VDC implementation and, a performance modeling methodology to support VDC implementation with Lean as a moderator, are some of the theoretical contributions to knowledge.

## 1.1 VDC AND LEAN

Lean Production is a concept from studies of the Toyota Production System (TPS), which is based on a philosophy of producing value as defined by the client without causing losses. Taj (2008) defined lean production “*as a manufacturing system without waste*” while waste is defined as “*anything other than the minimum amount of equipment, materials, parts, and working time that is essential to production*”. To accomplish this goal, Toyota conducted a series of internal changes by defining the two main pillars of lean production (Lichtig, 2006). The first pillar is “self-regulation,” intended to deliver flawless product quality by giving authority to employees to stop the production process if they find an error. The second pillar, “just in time,” states that the company produces a product only when there is an order for it in order to reduce inventories (Lichtig, 2006). This strategy arose because Toyota did not have the ability that other companies had to produce the variety and quantity of products its customers demanded. Toyota's main contribution is its creation of a system as a way to organize work to reduce costs and produce differentiated products in limited volumes (Liker, 2006; Morgan and Liker, 2006).

Koskela (1992) adapted the concept of lean production to the construction industry by formulating a new production philosophy called Lean Construction. Six years later, many people still thinking that lean appears to be more a method for manufacturing than for construction, but the goals of lean can be applied for every dynamic project (Howell and Ballard, 1998), such as construction projects (Sakal, 2005). The lean construction model production process is based on considering process flow (activities that do not add value) and conversion activities (activities that add value) to enable an analysis by emphasizing minimization and/or elimination of flow activities, which comprise most of the steps in the production processes in construction.

Lean Construction aims to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value (Koskela et al., 2002).

Howell (1999) mentioned *“the first goal of lean construction must be to fully understand the underlying “physics” of production, the effects of dependence and variation along supply and assembly chains. These physical issues are ignored in current practice which tend to focus on teamwork, communication and commercial contracts.”*

Moreover, lean supports the development of teamwork and a willingness to shift burdens along supply chains. Partnering relationships coupled with lean thinking make rapid implementation possible. Where partnering is about building trust, lean is about building reliability (Howell, 1999).

Managers must act based on three perspectives to generate a robust change within the organization: lean principles, VDC methodology, and organizational culture. The lean philosophy combined with the VDC methodology directly impacts organizational culture, so each area must contain strategic components (Alarcon et al., 2013).

VDC models are a new method to help the construction industry achieve lean construction by eliminating waste, reducing costs, improving productivity, and creating positive results within the project (Kunz and Fischer, 2011). The Lean philosophy is a conceptual framework for implementing VDC models because the impacts of VDC are associated directly with lean principles (Sacks et al., 2010). VDC models provide a framework to describe, monitor and manage changes to the product, process and organization throughout the project cycle (Kunz and Fischer, 2011).

Both Lean philosophy and VDC models promote practices moving in the same direction: integration, collaboration, and reduced cycle times, among others. However, a positive impact requires both the lean philosophy and VDC models simultaneously (Gerber et al., 2010). The combination of VDC modeling and lean philosophy is a very powerful tool (Dave et al., 2013; Gerber et al., 2010; Mandujano, 2016).

Khanzode et al. (2006), present a value investigation about how to apply VDC during all the stages of lean project delivery system (LPDS). They concluded that the tools, technologies and methods of the VDC framework provide the best toolset to accomplish the ideals of the LPDS.



Another example of the strong connection between VDC and Lean is a medical complex located in the US state of California, some of the benefits achieved by applying both methods were: virtually zero field conflicts between various systems, less than 0.2% rework, productivity improvement of more than 30% for the mechanical contractor, less than 2 hours per month spent on field coordination issues by the superintendent for the general contractor, only two field issues related request for information, and zero change orders related to field conflict issues (Khanzode et al., 2007).

Arayici, Kiviniemi, et al. (2011), provided a roadmap with detailed strategies, lean methods and techniques for successful BIM implementation. Some of their conclusions to achieve a successful implementation are: i) engage people in the adoption, ii) ensure that people's skills and understanding increases and companies building up their capacities, iii) to apply successful change management strategies, iv) work to diminish any potential resistance to change.

Four years later Khanzode (2010), presents four case studies (Camino Medical Office Building, Autodesk 1 Market Project, Stanford Medical Center, and PAMF MOB) and concluded that project teams and owners gain to benefit significantly by applying VDC tools and lean methods to manage the Mechanical, Plumbing and Electrical (MEP) Systems coordination process.

Another key study is the one presented by Sacks et al. (2010). They presented a matrix of interactions, negative and positive, between BIM and lean. The matrix is a full evidence of the potential synergies when planning their lean and BIM adoption strategies.

Gerber et al. (2010), analyzed three case studies to explore the relation of BIM and lean Construction. The authors concluded BIM and lean have a strong interaction between them.

My research follows a journal paper format. I present three papers organized into chapters 3 to 5 (Mandujano et al., Paper 1; Mandujano et al., Paper 2; Mandujano et al., Paper 3). Each of the papers contains its own abstract, introduction, research methodology,

discussion, conclusions and references. The three articles are connected in order to achieve the ultimate goal of this research. Next, I present the general methodology of this study.

## **2 RESEARCH METHODOLOGY**

### **2.1 HORSESHOE METHOD**

I adopted the CIFE “horseshoe” method to develop this research. This method defines a structured framework to plan and manage theoretical research in construction using a scientific method and the development of new engineering projects and methods (Kunz and Fischer, 2008). I used this framework to explain the steps I followed to conduct this research because it allows for an easy visualization of the entire project (Figure 2-1).

#### **2.1.1 PROBLEM**

Numerous investigations document inefficient and ineffective processes in VDC implementation which is currently based on anecdotes and beliefs about past projects that do not allow industry professionals to formalize lines of implementation and apply them throughout a project (Gao, 2011; Gao and Fischer, 2008; O’Ryan, 2011). Moreover, there are pieces of research that indicate the existence of synergies between lean and VDC. I defined the problem as follows:

*“The Architecture, Engineering and Construction (AEC) industry lacks theoretically founded and practical methodologies to identify strategies to successfully implement VDC and connect it with the Lean Construction”.*

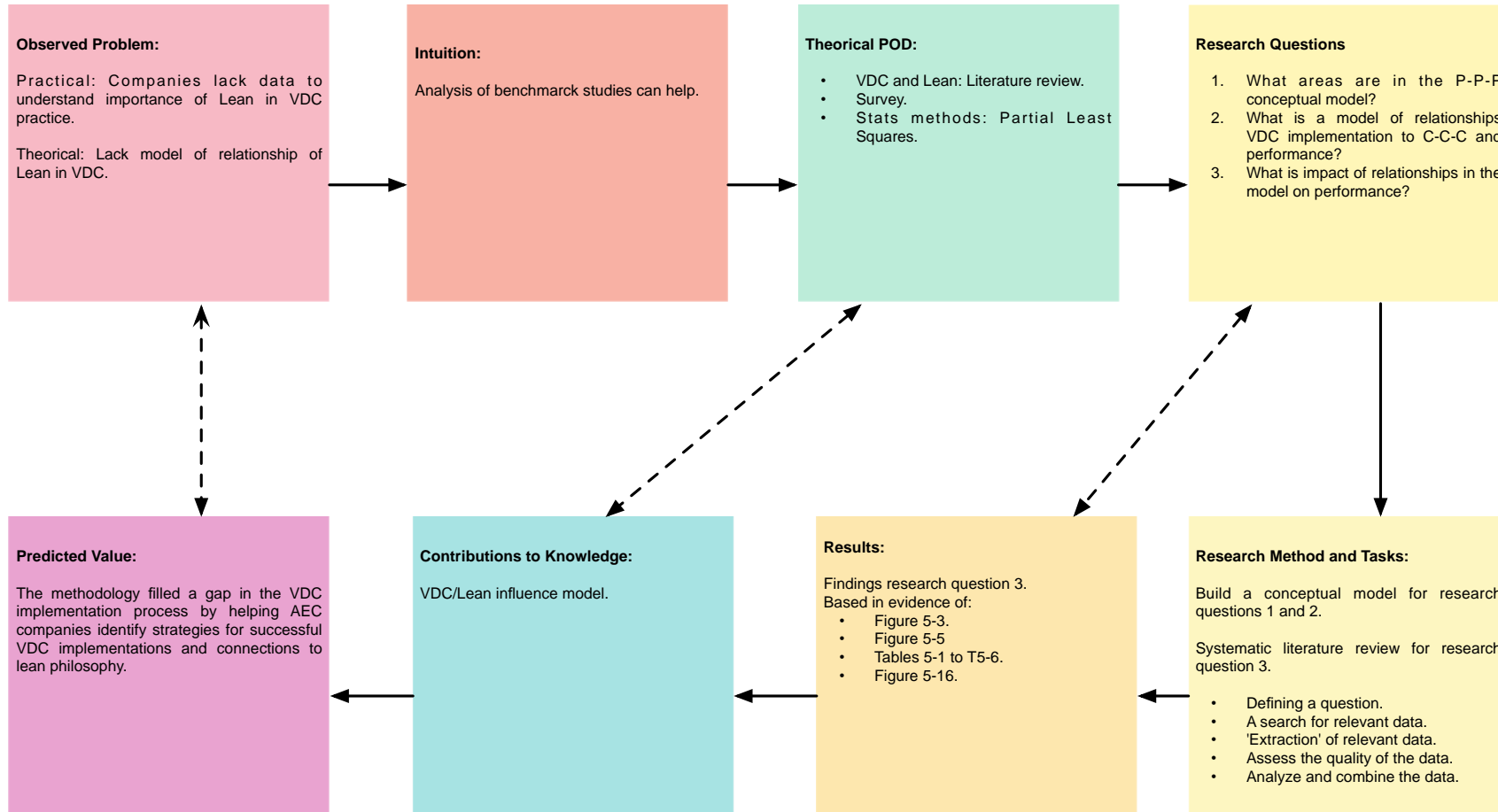


Figure 2-1 CIFE Horseshoe research method

### 2.1.2 INTUITION

I used a benchmarking method to address this problem. Costa et al. (2006), defined benchmarking as a systematic process of measuring and comparing an organization's performance against that of other similar organizations in key business activities. As competitors provide challenges in the marketplace, they also provide insight into how to reduce operating costs and increase efficiency (Atkin and Smith, 1999). Benchmarking must be an integral part of planning and an ongoing process of improvement to ensure a focus on the external environment and strengthen the use of factual information to develop plans (Camp, 1993).

The greatest benefits of benchmarking can include the resulting efficiency, active management involvement in the process rather than depending exclusively on the results, and improved reduction of waiting (Garvin, 1988). Therefore, the general purpose of benchmarking—its function as an assessment process—is to encourage continuous learning among managers and organizations (Barber, 2004).

In the AEC industry, benchmarking methodologies are primarily tools for continuous organizational improvement (Alarcon and Ashley, 1996; Alarcón et al., 2010; Atkin and Smith, 1999; Costa et al., 2006; El-Mashaleh et al., 2007; Lee et al., 2005; Park et al., 2005; Syuhaida and Aminah, 2009; Yeung et al., 2009). Implementing a performance measurement system that includes measures related to VDC implementation, with lean as a framework can drive continuous improvements of project processes.

### **2.1.3 THEORETICAL POD/GAP**

Despite the contributions made by the different studies (Fischer and Kunz, 2004; Gao and Fischer, 2008; Gilligan and Kunz, 2007; Khanzode et al., 2006; Kunz and Fischer, 2011) there is still a gap in the implementation process (Davies and Harty, 2013; Epstein, 2012; Gao, 2011; O'Ryan, 2011). Although multiple studies mentioned the quantitative or qualitative results related to VDC implementation most of these are still based on case studies (Davies and Harty, 2013; Forgues et al., 2012; Khanzode et al., 2008; Khemlani, 2009; Kong, 2010; Kunz and Fischer, 2011).

In addition, studies do not consider lean as a methodology separate from VDC as it has been linked to the results obtained from VDC implementation (O'Ryan, 2011).

There is a need for systematic methods that enable companies of Architecture, Engineering and Construction (AEC) to identify the best VDC and Lean implementation strategies as well as their impact on the results of the company and the project.

I used the following points of departure to guide my research:

- Current VDC implementation studies (Fischer and Kunz, 2004; Gao and Fischer, 2008; Gilligan and Kunz, 2007; Khanzode et al., 2006; Kunz and Fischer, 2011).
- Lean construction as a theoretical framework to analyze the impact of VDC implementation (Sacks et al., 2010).
- Current PLS studies (Hair et al., 2013).
- The Center for Integrated Facility Engineering survey as data to test the model proposed.

### 2.1.4 RESEARCH QUESTIONS

This study aimed to answer the following questions:

- 1. What areas are in the P-P-P conceptual model?*
- 2. What is a model of relationships VDC implementation to C-E-C and performance?*

Build a conceptual model for research questions 1 and 2.

- 3. What is impact of relationships in the model on performance?*

Systematic literature review for research question 3:

- Defining a question.
- A search for relevant data.
- 'Extraction' of relevant data.
- Assess the quality of the data.
- Analyze and combine the data.

Findings research question 3.

Based in evidence of:

1. Figure 5-3.
2. Figure 5-5
3. Tables 5-1 to T5-6 and Figure 5-16.

### 2.1.5 HYPOTHESES

This study has two hypotheses, which were explained in paper 3 (chapter 5). The hypotheses are:

1. Current implementation of VDC in projects and companies are suboptimal, with even the most apparently successful cases often missing many opportunities.

2. A systematic study of project and company implementation strategies can elucidate of the factors leading to a successful implementation a potential practical impact is that it may help managers design more effective implementation strategies.

### **2.1.6 GOALS OBJECTIVES**

The general objective of this study is to develop and validate a systematic methodology that enables AEC researchers to identify the best VDC implementation strategies and its impact on performance with lean construction as a moderator.

To achieve the general goal, I used the following research method:

- Develop a matrix with new interactions between VDC/Lean.
- Validation of hypotheses raised in the literature regarding the influence of BIM/VDC in Lean.
- Analyze the literature to find evidence of inefficiencies in VDC practice from a lean perspective.
- Characterization of the factors that affect VDC implementation.
- Design a model to represent conceptual aspects of VDC implementation, with lean as a moderator, to predict impact on project performance.

### **2.1.7 ORGANIZATION OF THE THESIS**

My thesis is divided in three chapter:

- *Chapter 3:* Chapter 3 had one specific objective: develop a matrix with new interactions between VDC and Lean. Next, I will explain the research method and tasks I followed.
  - I reviewed an extensive state of the art of VDC and lean construction through a databases search.

- With this knowledge I designed a matrix of 128 interactions between VDC and Lean.
  - Validation:
    - Testing hypotheses about interaction between VDC and lean construction were tested based in an extensive review of the literature.
- *Chapter 4:* This research had as specific objective find evidence of inefficiencies in VDC practice from a lean perspective. This phase was very important in my doctoral project because I found the way I incorporated lean. Chapter 4 had one specific objective: find evidence of inefficiencies in VDC practice from a lean perspective. Next, I will explain what were the research methods and tasks I followed.
  - Through a literature review about lean philosophy, lean office and lean IT, I found several areas of waste within VDC practice.
    - Validation:
      - Literature Review about VDC, Lean Philosophy, Lean IT and Lean Office.
- *Chapter 5:* Chapter 5 had two specific objectives: Characterization of the factors that affect VDC implementation and an impact evaluation model, as a tool to support VDC implementation with Lean as a moderator. I performed the following research methods and tasks.
  - I focused on the conceptual design model beginning with the characterization of the variables involved in the VDC implementation.



- Next, I explored mathematical models to find the one it will be useful for this research. After a deep exploration I found partial least squares (PLS) as the method to run my model.
- In addition to the previous literature review, I did another literature review to give a bigger support to the variables of my model. Based on the literature review, I designed the conceptual model.
- Having studied the survey previously, I started to design of the VDC/Lean influence model.
  - Validation:
    - Testing the conceptual model with the CIFE survey data: This survey was of paramount importance to this doctoral project. The CIFE aims to be the world's premier academic research center for VDC in AEC industry projects; to support exceptionally reliable engineering and management practices; and to plan, design, construct, and operate sustainable facilities. This is reported in chapter 5.
    - Descriptive statistics: In this research, I first explored the data using descriptive statistics to understand the current scenario related to VDC/BIM in the AEC companies. This step helped me to validated de data before running in PLS. This process is reported in chapter 5.
    - Bootstrapping (PLS): Finally, the results were validated through bootstrapping. This validation process is reported in chapter 5.
    - Literature review: I conducted a literature review to corroborate, remove, and add questions to the CIFE survey.

This provides a solid theoretical foundation for the proposed study. Developing a solid foundation for a research study is enabled by a methodological analysis and synthesis of quality literature (Barnes, 2005; Webster and Watson, 2002). Building a solid theoretical foundation based on quality resources enables researchers to better explain as well as understand problems and solutions that address actual issues with which practitioners are struggling (Levy and Ellis, 2006).

The CIFE survey was analyzed during all phases. In chapter 3, it helped me to understand the questions, answers and indicators. In chapter 4, the CIFE data helped me to know how to incorporate lean within the conceptual model. Finally, in the last phase I used the CIFE data to run the model

Also it is important to mention the sessions with committee members: Dr. Luis Fernando Alarcón and Dr. Claudio Mourgues helped me to refined and significantly improved each of the project objectives. They provided continuous, crucial feedback.

- Dr. Luis Fernando Alarcón is a Professor of Civil Engineering, Dept. of Construction Engineering and Management, Pontificia Universidad Católica de Chile (See <http://www.ing.uc.cl/cuerpo-docente/alarcon-luis-fernando/>).
- Dr. Claudio Mourgues is an Assistant Professor of Civil Engineering, Dept. of Construction Engineering and Management, Pontificia Universidad Católica de Chile (See <http://www.ing.uc.cl/cuerpo-docente/mourgues-claudio/>).

In addition to sessions with the committee, I was fortunate to had interviews with Dr. John Kunz, Dr. Lauri Koskela, and Dr. Bhargav A. Dave. These interviews enriched the results of the project.

- Dr. John Kunz is the Executive Director, Emeritus, of the Center for Integrated Facility Engineering (CIFE) in the Department of Civil and Environmental Engineering at Stanford University (See <http://web.stanford.edu/~kunz/>).
- Dr. Lauri Koskela is a Professor Of Construction and Project Management at the University of Huddersfield. Since 1991, Dr. Koskela has been involved in research on lean construction. He is a founding member of the International Group for Lean Construction (See <http://laurikoskela.com>).
- Dr. Bhargav A. Dave is a Senior Researcher, Department of Civil and Structural Engineering, Aalto University. He has several years of research and industrial experience in the areas of computing in construction, lean construction, and building information, modeling (See <http://people.aalto.fi/new/bhargav.dave>).

Figure 2-2 shows the research method and how the papers are connected to reach the final goal.

Chapters	Papers	Specific Objectives	Research Method	Results
Chapter 3	Paper 1	Develop a matrix with new interactions between VDC/Lean.	Find interactions between VDC/Lean. Research Method: Literature Review. Validate: Testing hypotheses about interaction between VDC and lean construction were tested.	New interactions between VDC/Lean.
Chapter 4	Paper 2	Find evidences of inefficiencies in VDC practice from a lean perspective.	Find Several types of waste within current VDC practice. Research Method: Literature Review. Validate: Literature Review about VDC, Lean Philosophy, Lean IT and Lean Office.	Keys to a successful VDC waste reduction process.
Chapter 5	Paper 3	Characterize the factors that affect VDC implementation.  Evaluate the impact of the model, as a tool to design the best VDC strategies with Lean as a moderator.	Develop a method to allow companies to assess VDC implementation with Lean as a moderator. Research Method: Literature Review, case studies, and PLS method. Validate: CIFE survey data, descriptive statistics, bootstrapping (PLS), literature review.	A performance modeling methodology that allows companies to assess VDC implementation strategies, including lean as a moderator.
Chapter 6	General Conclusions	Conclusions	Overview Contributions Future research and directions	

Figure 2-2 Research method

### **3 UNDERSTANDING THE INTERACTION BETWEEN VIRTUAL DESIGN, CONSTRUCTION AND LEAN CONSTRUCTION**

#### **3.1 INTRODUCTION**

The major challenges facing the architecture, engineering, and construction (AEC) industry have created a new way of working, forcing companies to use new methodologies such as virtual design and construction (VDC) (Fischer and Kunz, 2004). VDC is perceived as an approach that will help the AEC industry achieve better results by increasing the value of projects, reducing their costs, improving productivity, and creating other positive results (Eastman et al., 2011). A similar way, the lean construction philosophy can be used as a conceptual framework for VDC implementation because the impacts of VDC can be directly associated with lean construction principles (Sacks et al., 2010). A goal of this research is to elucidate and clarify the relationship between the BIM, concurrent engineering and metrics of VDC and its fourth element, Lean production management. There have been important advances regarding the synergies between building information modeling (BIM), as part of virtual design and construction (VDC) and lean construction (Eastman et al., 2011; Sacks et al., 2010). Despite these advances, previous studies have been focused primarily on product modeling and lean construction synergies, leaving aside the process and organizational components (Hamdi and Leite, 2012; Sacks et al., 2010).

I set the goal of this research to understand a) the full extent of the synergies between VDC, including BIM (product), process and organization modeling, and lean construction; b) the nature of these synergies (i.e., how strong or weak, direct or indirect, etc.); and c) the

reasons and conceptual explanations of why these synergies exist. To achieve the first goal, I did an extensive literature review, and evidence from the literature collected to populate the original matrix developed by Sacks et al. (2010). This literature review yielded a comprehensive update of the current extent of lean construction and VDC synergistic implementation in the industry. To achieve the second goal, the four hypotheses originally developed by Dave et al. (2013), concerning the potential nature of the relationship between lean construction and VDC, were tested to explore the nature of each interaction found within the matrix. After testing hypotheses, I analyzed the data about frequency of occurrence. To achieve the third goal, an analysis of the literature and the synergies identified carried out to explain the foundation and theoretical basis for the interactions observed. The achievement of these goals serves to guide the future implementation of VDC and lean construction, so as to provide insight that can lead to the development of more robust methods for implementing lean construction and VDC in the field. Using both theoretical and practical evidence, interactions between VDC and lean construction that will help the AEC industry and researchers create new strategies for joint implementation and plan their simultaneous implementation were examined in this study.

Before continuing the discussion, it is necessary to define two key concepts: VDC and the lean construction philosophy.

- VDC is the use of integrated multi-disciplinary (product, process and organization) performance models in design-and-construction projects to support explicit and public business objectives. The virtual models can complement and often replace physical models, and they can be built long before the actual product, organization, or process emerges in real life (Kunz and Fischer, 2011).
- The concept of lean production emerged from the study of the Toyota Production System (TPS) (J. Womack et al., 1990). The aim of TPS is to create value, as defined by the customer, while reducing waste (Lichtig, 2006; Liker, 1997, 2006). Koskela (1992) adapted the concept of lean production to the construction industry by formulating a new production philosophy called lean construction. Lean

construction refers to the application and adaptation of TPS's principles to construction (Sacks et al., 2010).

The remainder of this paper is structured as follows. Section 1 explains the difference between BIM and VDC. Section 2 presents the state of the art of VDC and lean construction management. Section 3 explains the research employed and the paper selection process. Section 4 presents the tests of the research hypotheses previously discussed in the literature. The paper concludes with a discussion of the findings and suggestions for further research.

### **3.1.1 BIM AND VDC**

The literature is ambiguous about the differences between VDC and BIM. Indeed, the terms VDC and BIM are sometimes used interchangeably (Liu et al., 2010). Organizations and researchers that refer to BIM as VDC and commercial companies that sell BIM as VDC have increased this confusion. As a result, some companies have sold BIM as simply a software platform, setting aside the core of the methodology: collaborative work.

The AEC industry and researchers in the field also have a number of views about what constitutes VDC (Fischer et al., 2003; Fischer and Kunz, 2004; Garcia et al., 2004; Khanzode et al., 2006; Kunz and Fischer, 2011). In this paper, the authors define VDC as defined by Kunz and Fischer (2011): "*the use of integrated multi-disciplinary performance models for design-and-construction projects to support explicit and public business objectives.*"

VDC is seen as a collaborative way of working that allows all stakeholders, including the owner, to share vital information throughout a building's entire life cycle. VDC is perceived as a collaborative approach that is enabled by technology. Without the necessary technology, the VDC method cannot be employed, and without the process (the series of activities that are necessary to achieve a result), the VDC technology is of limited value. To optimize the use of the technology, it is necessary to deploy the process. Traditional

methods use technology in isolation, whereas the VDC methodology uses technology in collaboration. In this context, all stakeholders have access to the same design, cost, and scheduling information at the same time. VDC is not simply an improved tool; it is an improved process intended to facilitate communication among participants at all levels.

The definition of BIM Eastman et al. (2011) seems to be slightly narrower than the definition of VDC and focuses on the production of a three-dimensional (3-D) intelligent virtual model that represents physical reality, hence excluding the process element. In contrast, VDC seems to focus on an overarching process that uses BIM (or 3-D modeling) as one of its tools but also includes organizational, process modeling tools and collaborative techniques as part of the approach. However, in practice, both these terms have been used in relation to the same broader definition. Eastman et al. (2011), presented an in-depth explanation of how BIM should be used in practice and presented examples of its application across the whole life cycle of a facility, while also emphasizing the aspects of collaboration and process change. It could be argued that both these terms ultimately reflect the same current understanding of this technology. However, the authors argue that this broader or inclusive BIM definition is a somewhat modern development and that the origins of the concept have deeper technological underpinnings.

Eastman (1975), published an article about a “Building Description System” in the AIA journal, and Aish (1986) described commonly known features such as 3-D modeling, automated drawing generation, parametric components, and others. In 1992, Van Nederveen & Tolman coined the term “building information modeling” to encompass these concepts. Aouad et al. (2005), in their definition of “nD” modeling, broadened the vision to include models that represent extended properties and behavior such as quantities, cost, energy, acoustics, etc. However, the focus still remained on modeling these behaviors rather than exclusively on the collaborative process of how the model was actually to be developed or used. It is only in the first edition of the BIM handbook (Eastman et al., 2007) and in the definition of VDC that one finds references to an overarching process and emphasis on industry-wide collaboration. This study partially explains the ambiguity that



exists around the use of the terms BIM and VDC, whether they are used to refer to a specific function (such as 3-D representation or a 5-D cost model) or a more overarching process of developing and communicating using the model.

It could be argued that the inclusion of the broader process and collaborative aspects has been necessary because the pure technological approach has not yielded the desired benefits. As evidence has emerged from case studies and industry practice (Eastman et al., 2007; Fischer and Kunz, 2004), the importance of addressing the broader process-related aspects has been recognized and included in the definition of BIM. The authors would like to suggest that while academia and industry have now realized the value of including people (organizational) and process aspects, future research can ensure that the chosen process model is based on a sound foundation and has the potential to improve the core functions of the industry.

### **3.2 STATE OF THE ART OF VDC AND LEAN MANAGEMENT**

This section uses the terms BIM and VDC consistently with the way used by the referenced pieces of research. This may create some confusion, which depicts the problem discussed earlier, but we believe it is necessary to keep the original references to reduce research biases. Preliminary research indicates that there are positive synergies between lean construction and BIM that span the entire construction life cycle, supporting the process from conceptual design to construction or from handover to use (Bhatla and Leite, 2012; Enache-Pommer et al., 2010; Epstein, 2012; Gao and Fischer, 2008; Gerber et al., 2010; Hardin and McCool, 2015; Reddy, 2011; Sacks et al., 2010; Sands and Abdelhamid, 2012; Tommelein and Gholami, 2012). Sacks et al. (2010), concluded that there are strong synergies and many interactions between lean construction principles and BIM functionalities. BIM and lean construction appear to share the same goal: enhancing construction process performance by eliminating waste and improving client value. In North America, adoption of BIM has increased significantly over the last five years (McGraw-Hill, 2009). This growth is attributed to the multiple benefits BIM provides

(Khanzode et al., 2006), which can be accrued in both the short and long term, increasing the speed of the preconstruction and construction stages, according to (Gao and Fischer, 2008). BIM models are viewed as supporting the construction industry in achieving lean construction principles by eliminating waste, simplifying procedures, and speeding up production within projects (Ningappa, 2011). Although BIM and lean construction can be implemented independently, to achieve their greater potential, it is important to consider both approaches simultaneously (Hamdi and Leite, 2012). Several case studies have demonstrated the strong synergies between BIM and lean construction (Eastman et al., 2011; Khanzode et al., 2007; Sacks et al., 2010).

Coates et al. (2010) stated “ *applying [the] concepts of BIM and lean simultaneously allows for the adoption of BIM with a greater understanding of the efficiencies to be gained and how the technology integrates within the construction process.* ” This finding means that the potential effect of the joint implementation of BIM and lean construction is greater than the sum of its parts, consequently improving project performance.

By means of a case study, Khanzode et al. (2006) demonstrated how it is possible to jointly implement VDC and a lean project delivery system (LPDS) during the initial phases of a project. They emphasized that LPDS provides a framework for structuring the project implementation process but does not provide the tools necessary to achieve the objectives of a lean production system (Khanzode et al., 2006). The tools, technologies and methods of VDC represent the best way to achieve the ideals of LPDS. The early implementation of VDC allows for improved workflow (Kala et al., 2010), the ability to coordinate work in the execution stage (Gilligan and Kunz, 2007), and real transparency throughout the process (Sacks et al., 2009).

It has been stated that to successfully implement BIM and lean construction, it is necessary to enter into a process of continuous improvement (Dave et al., 2013), which, in most cases, requires a major management process change (Cerovsek, 2011; Greenwald, 2012). VDC involves much more than simply implementing new software; it is a new way of working. VDC requires a move away from a traditional workflow, with all parties

sharing and effectively working with a common pool of information. Lean and VDC implementation involve three components (Alarcon et al., 2013) (Figure 3-1). The philosophy and culture of lean construction and VDC management principles have great synergies and share many main ideas: collaboration in design and construction, optimization of the whole system, as well as participation and involvement of the end users. These are all facilitated by VDC and lean construction implementation.

LPDS promotes the early involvement of all parties and the concurrent design of all project aspects, which are also goals of VDC. On the other hand, VDC provides powerful technology to sustain the lean implementation effort. VDC eliminates waste (Khanzode et al., 2007) but also improves workflow for many actors, even those who do not use VDC directly (Eastman et al., 2011).

VDC encourages and provides a path for the sharing of information among the stakeholders. One enables the other: the technology enables the process and the process enables the technology, making it likely, possible, and even necessary (Deutsch, 2011).

Although each approach can be carried out independently, to achieve the greater potential, it is necessary to consider the culture, philosophy, and technology jointly. This makes the potential for VDC and lean construction implementation greater than the sum of their parts, consequently improving project performance.

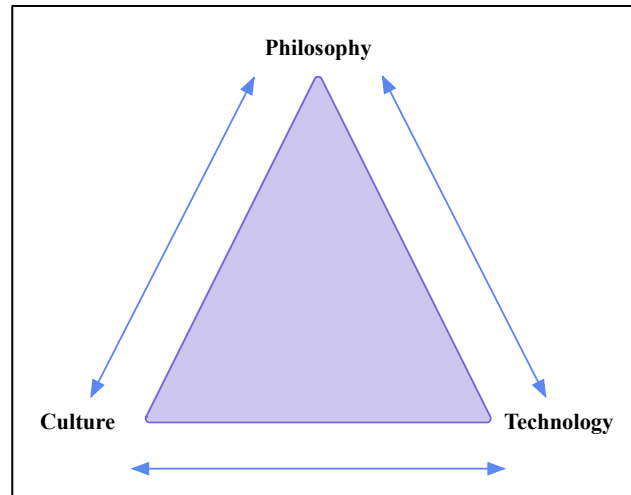


Figure 3-1 Lean/ Virtual design and construction implementation components

### 3.3 GENERAL METHODOLOGY AND ARTICLE SELECTION

The next research task was to analyze relevant articles published during the period from 2000 to 2013 to identify new synergies between VDC and Lean through a systematic search of many electronic databases. To limit the scope of the literature review, the authors performed a keyword search of top journals, databases, and conference proceedings. The search was carried out using three keywords: BIM, VDC, and lean. These keywords were chosen because the authors sought to identify the essential components of the literature on VDC and lean construction.

I categorized the studies according to their methodologies: surveys/interviews, case studies, literature reviews, and implementation guides. The literature on VDC implementation covered many important aspects, including but not limited to its benefits and obstacles, synergies between lean construction and VDC, its current status, implementation strategies, and the impacts of VDC in the AEC industry. The database found a total of 143 articles that contained the selected keywords in their abstracts.

The first inclusion criteria selected systematic literature reviews that used and described systematic methods that were relevant to VDC and lean, and contained interactions between VDC and lean construction. Through literature review, I found 120 articles selected based on their abstracts. The full texts of the 120 articles were evaluated based on their full texts. A total of 84 articles from 53 different databases were finally selected and included in this literature review. The process is summarized in Figure 3-2.

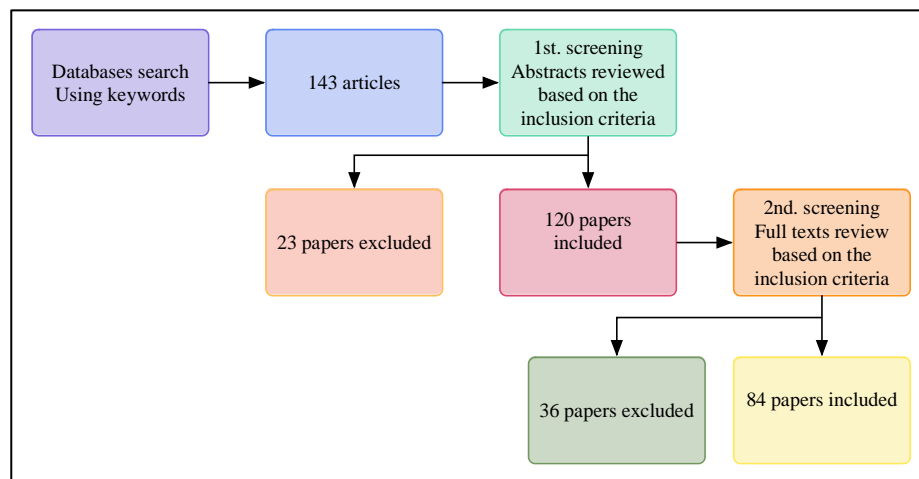


Figure 3-2 Summary of the review article process

Figure 3-3 shows the international distribution (in percentages) of the reviewed research articles, publications (books and academic/applied papers), and relevant standards and Internet sources.

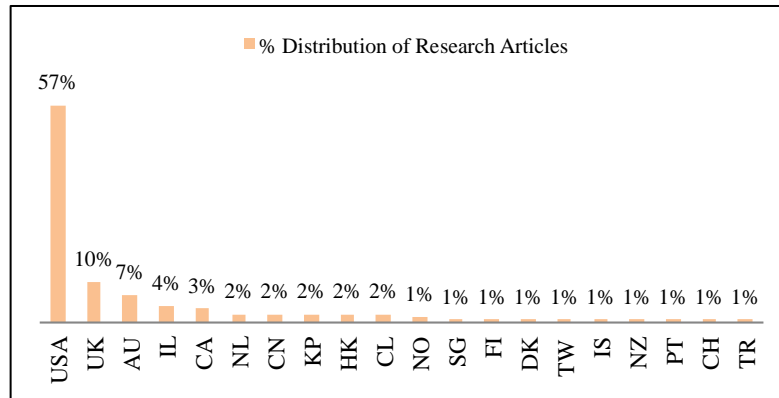


Figure 3-3 Distribution of research articles

The majority of these articles are from the Center for Integrated Facility Engineering (CIFE), *Automation in Construction*, and the *Journal of Construction Engineering and Management*. A substantial difference in the number of published articles can be observed between 2000 and 2013 (Figure 3-4). However, the total number of articles is still moderate, considering that every journal provides less than one relevant article per year, on average. The authors found few articles published between 2002 and 2003. The greatest number of articles (23) was published between the years 2010 and 2011.

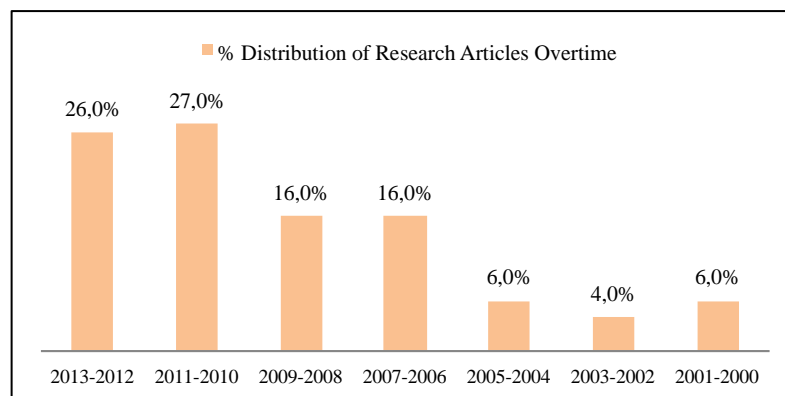


Figure 3-4 Distribution of research articles

### 3.4 DEVELOPING THE INTERACTIONS MATRIX

Using the information described above, a matrix was developed (Table 3-1) showing 224 interactions between VDC and lean construction, some of which, in one way or another, were mentioned by Sacks et al. (2010), including those referred to as “not found yet.” (The full list of interactions can be accessed at (Mandujano, 2015)). The numbers in Table 3-1 represent types of interactions.

The following aspects were considered to create the tables and matrix:

- For the VDC features, the authors focused mostly on those mentioned in their previous literature review (Azhar et al., 2008; Eastman et al., 2011).
  - A. **Visualization of the product:** VDC models can be observed from very early stages.
  - B. **Production of construction documents:** It is easy to generate drawings for various building systems.
  - C. **Analysis of design options:** It is easy to analyze many design alternatives.
  - D. **Supply chain management:** VDC allows for better supply chain management.
  - E. **Design checking:** All major systems can be visually checked for interferences.
  - F. **Code reviews:** Departments managers may use VDC for their review of building projects.
  - G. **Construction planning/4-D modeling:** VDC can be effectively used to effectively deliver schedules for all building components.

Table 3-1 Virtual design and construction features (VDC) vs. lean construction principles

VDC FEATURES				PRINCIPLES FOR FLOW PROCESS DESIGN AND IMPROVEMENT											PROBLEM SOLVING		DEVELOPING PARTNERS	
				REDUCE THE NON VALUE- ACTIVITIES	CUSTOMER REQUIREMENTS	REDUCE VARIABILITY	REDUCE TIME	SIMPLIFY	FLEXIBILITY	STANDARDIZE	TRANSPARENCY	CONTROL THE PROCESS	BUILD CONTINUOUS IMPROVEME	BALANCE FLOW	BENCHMARK	GO AND SEE FOR YOURSELF	DECIDE BY CONSENSUS	CULTIVATE AN EXTENDED NETWORK
	POP	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o		
A) VISUALIZATION OF THE DESIGN	o			46, 145	53, 139, 168, 180	4,5,9,24, 86, 126	1,7,56, 126, 127, 195	7, 73	57, 73	7	1,9,11,24,53 ,69, 78, 132, 137, 164	1, 69, 221	53, 69, 73, 191, 192, 193	4,9, 69	69	11, 129, 184	45,57, 94, 129	53,57, 94
B) PRODUCTION OF CONSTRUCTION DOCUMENTS	o			22, 109, 115, 121, 153*, 218	21, 167, 174	16,22, 102, 107, 115, 190, 209, 214	14,21,48,58,60,6 7, 87*, 90, 110*, 115, 153*, 159, 211*, 223	28, 60, 72*, 153*, 194*	22, 93, 200, 202, 208	28, 89, 199, 215	21, 85, 115, 200	44,47, 106, 140	44, 85, 152, 173, 207, 214, 222	62, 92, 115	140	178	21,44 91	21,44,55, 85, 198, 216
C) ANALYSIS OF DESIGN OPTIONS	o			74, 137	49,51,53, 168	24, 214	14,48, 81, 96	48	51, 75*	51, 82*	49,51, 133, 137, 166	37	29, 74, 178	96		51	45,49,51,10 3, 166, 219	59, 175
D) SUPPLY CHAIN MANAGEMENT		o		64, 187	123	123	58, 119, 186, 205	64,65	125	47	47	64,65, 106	205	205				
E) DESIGN CHECKING	o			74, 179	53, 168	30, 155	20, 154, 156	15	15	140	6,20, 155, 179	37, 106	6, 140, 183			155	63	63, 104
F) CODE REVIEWS		o			88		52, 88, 195	124			52,53,54	195	124			124		94
G) FORENSIC ANALYSIS		o			41		18,41	18	113	112	18,41,53,54							
H) FACILITIES MANAGEMENT		o		2	40	170, 181	39, 171, 181	2,40, 112	39	43	2,39,53,54, 161, 171	2,42, 111	42, 162	112	61	161	2	112
I) QUANTITY TAKEOFF AND COST ESTIMATING/ 5D MODELING		o		160, 177, 189	32,33,38, 180	32,34, 158, 189	7,25,26,32,34,35, 36,38, 158, 160	7,25, 158	25, 157	7	25,34	32, 157	32, 177	38	31	157	38	210
J) CONSTRUCTION PLANNING / 4D MODELING			o	12, 131, 145, 146	13, 79, 169, 172, 180	5,9,12, 203	5,8,12,17, 68, 130, 133, 136, 146, 185, 188, 212	5,8, 130, 141	5,8,15, 148	8, 133, 148	5,66,68, 79, 80, 114, 131, 138, 143, 144, 196, 201	5,66, 68, 138, 176	13,66, 77, 163, 222	9,66, 142, 149	31, 77	66, 79	13, 68, 79, 80, 142, 147, 150, 151	13, 197, 204, 216
K) ORGANIZATIONAL MODELING			o	213, 224		70, 213	83, 213	213	213	99	83, 213	83, 213	83, 213	213	31, 83			
L) BUILDING PERFORMANCE ANALYSIS		o	o	108	120	4, 108	3,28, 71, 98	3, 98	3, 71, 220	97, 100	3,28,50, 98, 135, 206, 220	3, 100	27, 98, 122	98	31, 98	120	27, 98	108, 120
M) ONLINE COMMUNICATION PRODUCT/PROCESS			o	11,46	45, 84, 95	11,19, 209	10,15,45, 76, 95, 101, 105, 182	10,11,45	11, 105	45	10,11,45, 80, 84, 95, 101, 105	10,11, 101, 105	10,15,45, 116	45, 95, 101, 105	105	45, 80, 105, 104	10,11,45, 76, 80, 94, 95, 105, 165	10,11,45, 84, 94, 95, 116, 117, 118, 165, 216, 217

Note: The numbers in the cells are indices of the cell content explanations provided in the evidence found. To access to the full list, please visit: Mandujano, 2015. Numbers with \* symbols represent negative interactions.



- H. **Organizational modeling:** VDC can be effectively used to effectively design the organization modeling.
  - I. **Building performance analysis:** VDC allows analysis of some other types of performance models, such as energy performance, sustainability, and post-occupancy models.
  - J. **Online communication product/process:** VDC allows online reviews and markup of design and construction documents.
- The lean construction principles and their definitions were chosen based on Koskela (1992) and Sacks et al. (2010).
    - a. **Reduce the non-value added activities (also called waste):** Reduce the non-value added activities (also called waste) that take time, resources, or space but do not add value.
    - b. **Customer requirements:** Increase the output value through systematic consideration of client needs.
    - c. **Reduce variability:** Reduce variability by controlling the uncertainties in the process.
    - d. **Reduce time:** Reduce the cycle time.
    - e. **Simplify:** Simplify, minimizing the number of steps, and links.
    - f. **Flexibility:** Increase output flexibility.
    - g. **Standardize:** Reduce the variables that can affect the delivery results.
    - h. **Transparency:** Increase process transparency.
    - i. **Control the process:** Focus control on the complete process.
    - j. **Build continuous improvement:** Create a culture of continuous improvement from the bottom up and where valuable processes occur.
    - k. **Balance flow:** Balance flow improvement with conversion improvement.
    - l. **Benchmark:** Continuously referencing processes.
    - m. **Go and see for yourself:** Go and see for yourself to understand the situation.

- n. **Decide by consensus:** Make decisions slowly by consensus, thoroughly considering all options.
  - o. **Cultivate an extended network:** Respect your network of partners by challenging them and helping them to improve.
- The types of waste that VDC–lean construction interaction could reduce (Morgan and Liker, 2006) and the lean construction techniques that the industry could apply to improve VDC adoption. The full list of interactions can be accessed at Mandujano (2015).

Waste:

- **Overproduction:** Producing more or earlier than the next process needs.
- **Waiting:** Waiting for materials, information, or decisions.
- **Conveyance:** To take or carry someone or something to a particular place.
- **Processing:** Unnecessary processing on a task or performing an unnecessary task.
- **Inventory:** A build-up of material or information that is not being used.
- **Motion:** Excess motion or activity during task execution.
- **Correction:** Inspection to catch quality problems or to face an error already made.

Lean techniques:

- **Just in time:** A production system that manufactures and delivers just what is needed, only when necessary, and the right amount.
- **Total quality control:** A management approach in which each is responsible for continuous quality improvement so products and services meet customer expectations.
- **Total productive maintenance:** Everyone in a production process always is able to perform his or her required tasks.

- **Employee involvement:** To avoid waste associated with division of labor, multi-skilled and/or self-directed teams are established for product/project/customer-based production.
- **Continuous improvement:** A key idea is to maintain and improve the working standards through small, gradual improvements.
- **Benchmarking:** A focus on business processes, rather than the technologies used in them.
- **Time-based competition:** Compressing time throughout the organization for competitive benefit.
- **Concurrent engineering:** Design of products and services in which developers consider sets of ideas rather than single ideas.
- **Value-based strategy:** Conceptualized and clearly articulated value as the basis for competing.
- **Visual management:** The goal is to render the standard to be applied, such that a deviation from the standard is immediately recognizable by anybody.
- **Re-engineering:** Reconfiguration of processes and tasks, especially with respect to implementation of information technology.

Table 3-2 shows the frequency of occurrence of each interaction of Table 3-1. The columns show the total occurrence for each VDC feature, and the rows show the totals for the lean principles. We can see that construction planning / 4d modeling (J) is the VDC feature most mentioned in our literature review. Followed by production of construction documents. Also, reduce time (d) and transparency (h) is the most mentioned lean principles allowed by VDC. The interactions more mentioned were: planning / 4d modeling (J)- reduce time, and production of construction documents- reduce time.

Table 3-2 Frequency of interactions

ID	a	b	c	d	e	f	g	h	i	J	K	l	m	n	o	Total
A	2	4	6	6	2	2	1	9	3	6	3	1	3	4	3	55
B	5	3	8	10	2	5	4	4	4	7	3	1	1	3	6	66
C	2	4	2	4	1	1	1	5	1	3	1		1	6	2	34
D	2	1	1	4	2	1	1	1	3	1	1					18
E	2	2	2	3	1	1	1	4	2	3			1	1	2	25
F		1		3	1			3	1	1			1		1	12
G		1		2	1	1	1	4								10
H	1	1	2	3	3	1	1	6	3	2	1	1	1	1	1	28
I	3	4	4	10	3	2	1	2	2	2	1	1	1	1	1	38
J	4	5	4	12	4	4	3	12	5	5	4	2	2	8	4	78
K	2		2	2	1	1	1	2	2	2	1	2				18
L	1	1	2	4	2	3	2	7	2	3	1	2	1	2	2	35
M	2	3	3	8	3	2	1	8	4	4	4	1	4	9	12	68
Total	26	30	36	71	26	24	18	67	32	39	20	11	16	35	34	

### 3.5 TESTING THE FOUR HYPOTHESES PREVIOUSLY DISCUSSED IN THE LITERATURE

Dave et al. (2013), presented four hypotheses to explain how lean construction and BIM relate to each other (hypotheses 1-4 in Table 3-3). I tested these hypotheses with the evidence from practice and/or research presented in the literature. I hypothesized that VDC allows for more interactions with lean construction (hypotheses a-d in Table 3-3).

Table 3-3 Frequency of hypotheses

HYPOTHESIS NUMBER	HYPOTHESIS DESCRIPTION	FREQUENCY OF REFERENCES IN LITERATURE	
		BIM	VDC
2	BIM enables lean construction processes, which contributes indirectly to lean construction goals.	27	
b	VDC enables lean construction processes, which contributes indirectly to lean construction goals.		71
1	BIM contributes directly to lean construction goals.	19	
a	VDC contributes directly to lean construction goals.		73
4	Lean construction processes facilitate the adoption and use of BIM.	19	
d	Lean construction processes facilitate the adoption and use of VDC.		66
3	Auxiliary information systems, enabled by BIM contribute directly and indirectly to lean construction goals.	12	
c	Auxiliary information systems, enabled by VDC contribute directly and indirectly to lean construction goals.		67

Table 3-3 shows the frequency of the hypotheses vs. the frequency found in the literature about VDC. The hypothesis that “BIM enables lean construction processes that contribute indirectly to lean construction goals” occurred with the highest frequency, followed by hypotheses 1, 4, and 3. In the fourth column, the hypothesis that, “VDC enables lean construction processes, which contributes indirectly to lean construction goals” occurred with the highest frequency, followed by hypotheses a, d, and c. The results suggest that to achieve more synergies between lean construction and VDC, including BIM (product), process and organizational modeling, it is necessary to use the entire VDC framework. This allows more positive interactions between lean and VDC, versus a similar situation that only includes an interaction between lean construction and BIM.

### 3.6 DISCUSSION

After clarifying the concepts, as shown in table 3-1, 224 interactions between VDC and lean construction were identified in the literature. These allow for the development of new VDC implementation strategies and also provide a broader picture for the construction industry to implement more holistic and substantial improvements in every project phase. The new interactions identified in the literature can help to complete the matrix proposed by Sacks et al. (2010) and create new implementation strategies.

Among the findings from table 3-1:

- Co-locating the design and detailing teams so that detailers work side by side allows them to construct designs virtually and resolve conflicts or issues immediately, further facilitating highly integrated (e.g. “big room”) project delivery.
- Extended networks that increase collaboration among firms are more effective at implementing models across organizations.
- 4-D improves efficiency and safety. It can help identify several problems before the construction starts.
- 5-D models, which connect 3-D models to databases for quantity takeoff, location-based planning, and scheduling; this makes it easier to visualize quantities and integrate them into schedules and cash flows.

Our research showed that without the VDC framework, these interactions would be achieved to a lesser extent. This finding was supported by the previously discussed hypotheses as shown in Table 3- 3. The interactions frequently mentioned, with a similar frequency in the literature and practice, were the following:

- Production of construction documents to reduce time (Bd),
- Quantity takeoff and cost estimation/5-D modeling to reduce time (Id),
- Construction planning/4-D modeling to reduce time (Jd),

- Construction planning/4-D modeling for transparency (Jh), and
- Online communication product/process for cultivation of an extended network (Mo).

The interactions listed above have strong and direct impacts among them. First, with the use of VDC, the process as a whole becomes more efficient (Khanzode et al., 2006). The production of construction documents becomes automated, which reduces the amount of time for documents to be delivered (Sacks et al., 2010). The use of construction planning/4-D modeling and cost estimation/5-D modeling helps to reduce time and add value to projects. Moreover, the use of construction planning/4-D modeling improves project transparency because 4-D modeling permits the visualization of the sequence of project activities; all issues are identified prior to construction. This results in cost and time saving on site because of effective planning (Eastman et al., 2011). VDC is a methodology based in part on technology; a clear example of this is the interaction between online communication product/process and cultivation of an extended network. The use of tools, such as iRoom onsite, plasma screen monitors, iPads, and/or tablet PC's loaded with the latest VDC model (Hamdi and Leite, 2012), allows for coordination and communication among all stakeholders. The level of visualization achievable is high because it is close to the actual and most updated model version and is available to different levels of the hierarchy, especially for on-site workers (Hamdi and Leite, 2012).

This research, as well as Sacks et al. (2010), identifies negative interactions between VDC and lean. The negative interactions found are:

- Production of construction documents – reduction of non-value adding activities (Ba),
- Production of construction documents – reduction of time (Bd),
- Production of construction documents – simplicity (Be);
- Analysis of design options – flexibility (Cf), and
- Analysis of design options – standardization (Cg).

The negative interactions can be interpreted in several ways. While VDC allows a range of benefits throughout the entire project, the negative interactions are the result of continuing to see VDC as a technology that puts aside the collaborative view (processes and people). An example of this is the interaction of “Production of Construction Documents” and “Reduce Non-Value Adding Activities.” In many cases, the models that are sent from one entity to another contain many inconsistencies. Such inconsistencies create extra work during the production of documents. One key result is the interaction between “Production of Construction Documents” and “Reduce Time.” This interaction has a strong and direct impact, but an abuse of the ease with which drawings can be generated can lead to more versions of drawings (Sacks et al., 2010) and, as a consequence, an increase in processing time (Madsen, 2008). This result encourages caution when producing construction documents or analyzing design options. The ease with which “Production of Construction Documents” can be detailed creates a negative interaction with “Simplicity.” Too much detail in the construction documents increases complexity rather than simplicity (Hartmann et al., 2007; The CRC for Construction-Innovation, 2009). Finally, the interaction of “Analysis of Design Options,” “Flexibility,” and “Standardize” is a clear example of the need to incorporate lean construction throughout VDC practice. Mandujano et al. (2016) found several types of waste within current VDC practices and suggested that if teams use lean construction methods and focus on elimination of these types of waste (i.e., non-value-added processing, excess motion, excess inventory, waiting, and overproduction) teams can improve their VDC practices dramatically. Mandujano et al. (Paper 2) suggests the use of protocols for sharing models, BIM libraries, meeting protocols, and quality protocols to minimize waste within VDC practice; and as shown in this study, it can enhance or reverse negative interactions.



### 3.7 CONCLUSIONS

This research distinguished between VDC and BIM. This step was crucial to clarify the ambiguity between these terms. Although significant advances have been made with regard to the synergies between BIM and lean construction, a gap in the theory existed in terms of how to extend these interactions throughout the VDC methodology including BIM (product), process and organization modeling. The results of this study contribute to a better understanding of the impact of simultaneous implementation of lean construction principles and the VDC approach on various stages of construction projects. Identifying the interrelationship of management principles with uses and actions performed through VDC provides a broader picture. Identified the interrelationship allows the AEC industry to take a more holistic approach that can help to obtain substantial improvements in every project phase by increasing the effectiveness of the methods through better alignment with relevant management principles. The distinction between the definitions of BIM and VDC is important to developing a better understanding of the methods and their associated management principles. A significant number of interactions between lean management and VDC were identified in the literature that can help to complement the findings of previous studies and create new implementation strategies in the future. This research showed that without the VDC framework, these interactions would be achieved to a lesser extent. To support this premise, the authors tested the interaction hypotheses previously mentioned in the literature.

Future research should direct attention toward understanding the nature of these interactions in further detail and increasing the frequency of interactions between VDC and lean construction. As previously mentioned, although VDC and lean management implementation initiatives can be carried out independently; however to achieve the greater potential of these improvement efforts, the results indicated that it is necessary to consider the important synergies that their interactions offer. VDC provides numerous benefits throughout construction projects but requires a framework—in this case, lean

construction—for regulation throughout the implementation of the methodology. Only in this way can companies and projects take full advantage of the benefits that VDC and lean construction offer. Much remains to be performed in the area of VDC and lean construction. The AEC industry is constantly changing, and needs are becoming greater.

This research is part of a research project that aims to identify VDC implementation strategies from a lean construction perspective and their impact on project performance. This paper reports on the first stage of a research study on the identification of the best VDC implementation strategies.

## **4 IDENTIFYING WASTE IN VIRTUAL DESIGN AND CONSTRUCTION PRACTICE FROM A LEAN THINKING PERSPECTIVE**

### **4.1 INTRODUCTION**

Great advances have forced and enabled the construction industry, considered one of the most resistant to change, to use new methods that allow it to survive (Concha et al., 2015). Virtual Design and Construction (VDC) and lean construction allow the construction industry to face different challenges (Khanzode et al., 2008; Khanzode et al., 2006). Multiple investigations converge in the potential that is achieved by implementing both initiatives together (Gerber et al., 2010; Sacks et al., 2010). While VDC and lean construction, have brought great benefits to the Architecture, Engineering and Construction industry (AEC), it appears that some efforts have focused on seeing lean processes as an approach merely for production (Rischmoller et al., 2006). Using evidence from the literature, we found several waste areas within VDC application that have been identified. This research aims to extend lean construction as an initiative that can "branch" throughout all processes of VDC, including information flow.

As a starting point, we define the two concepts for the specific purposes of the study:

#### **4.1.1 VIRTUAL DESIGN AND CONSTRUCTION**

Kunz and Fischer (2011) define VDC models as: *"The use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives."* The Center for Integrated Facility Engineering (CIFE) indicates that a project

is a set of information flows that can be modeled and represented in a computer using symbolic representations of Products, Organizations, and Processes (P-O-P) (Khanzode et al., 2006). VDC allows building models of P-O-P early before a large commitment of time or money is made to a project (Khanzode et al., 2006).

VDC methodology includes use of Building Information Modeling (BIM). Researchers have viewed and defined BIM from different perspectives. Eastman et al. (2007) defined BIM as a modeling technology and associated set of processes to produce, communicate and analyze building models. McGraw-Hill (2009) emphasized that BIM is the process of creating and using digital models for design. That study also noted that BIM serves as a shared knowledge resource for information about a facility and a reliable basis for decision-making.

VDC methods include BIM, Integrated Concurrent Engineering (ICE), metrics and lean-based production management. There is an explicit process to apply VDC: Plan (use of one or several of the methods), Do (apply the method), Check (that the BIM or ICE session of plan conforms to plan) and Act, i.e., take next steps. Although sometimes the terms VDC and BIM are used interchangeably, BIM represents the form/scope of the product, which is crucial but only one part of the VDC framework (Kunz and Fischer, 2011). When we reference VDC, we refer to the entire framework method (P-O-P), which has BIM as a part of the product definition (Figure 4-1). BIM relates to other methods and tools such as production models, critical path method (CPM) schedules, decision models, organizational models and 4D models (4D refers to the four dimensions of X, Y, Z and time, i.e. 4D is 3D BIM+ schedule (time)).

In this analysis, we focus on VDC as a process. A process is a structured, measured set of activities designed to produce a specified output. It implies a strong emphasis on how work is done within an organization, especially the “Plan” and “Check” activates, in contrast to a pure product focus emphasis on what (Davenport, 1993). VDC includes models, but it also includes properties of model elements, or data, as well as processes to plan, create, check and act using models.

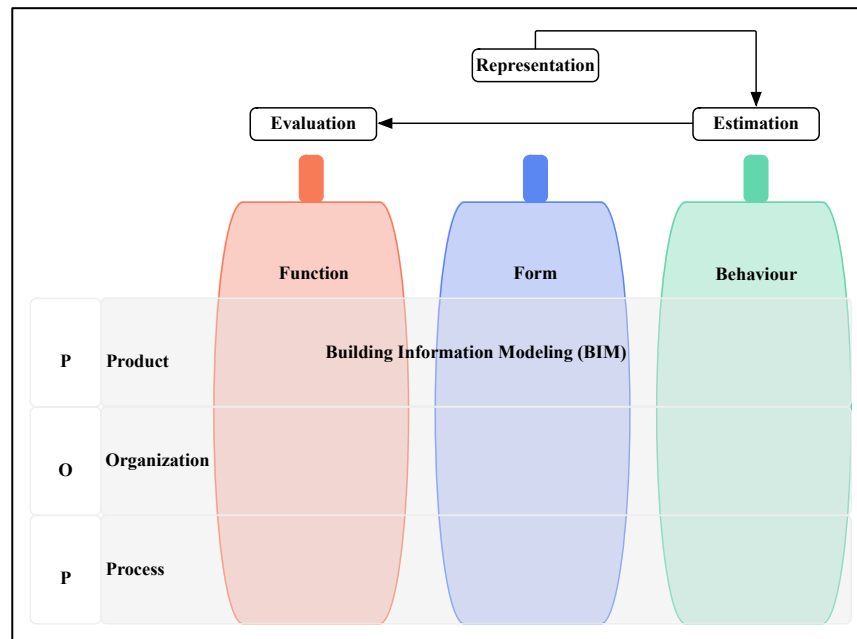


Figure 4-1 The three components of the P-O-P framework. Source: Alarcón and Mourgues (2010).

#### 4.1.2 LEAN PHILOSOPHY

Lean is a management philosophy that provides methods to identify waste and uses a number of tools and principles to minimize or remove waste. Instances of waste can be found at any stage of the project, from the beginning of design through the construction phase. The more waste is eliminated, the better the results (Plenert, 2011). Koskela (1992) adapted the concept of lean production to the construction industry by formulating a new production philosophy called “Lean construction.” Although, there are studies that point out how the impacts of VDC can be directly associated with lean principles (product view), this paper suggests that lean construction methods can help to reduce waste in the

information flow (process view) of VDC practice. Figure 4-2 shows the graphical representation of waste in VDC practice.

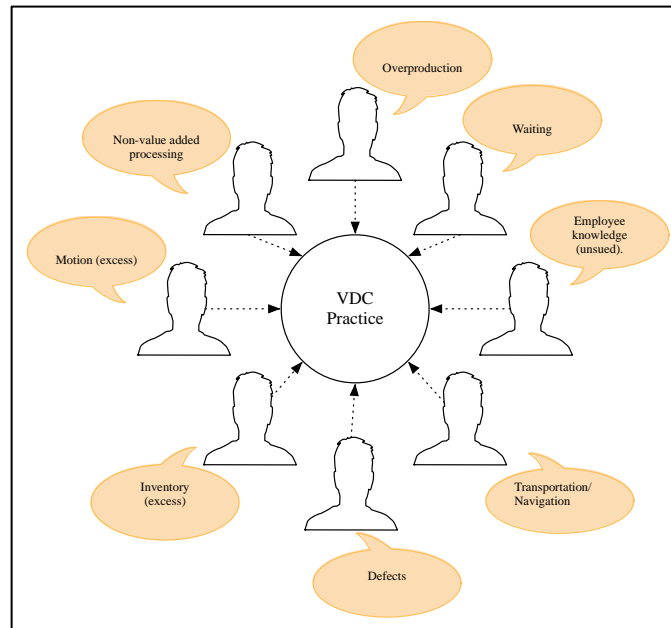


Figure 4-2 Waste between VDC practice (Self-elaboration).

### 4.1.3 LEAN IT

Manufacturing has been a reference point and a source of innovations in construction for many decades (Koskela, 1992). In the early twenty-first century, a new approach called lean information technology (IT) emerged, which aims to identify and eliminate waste within IT development processes, focusing primarily on information flow. Bell and Orzen (2010) defined lean IT as: *“the use of lean principles, systems and tools, to integrate, align, and synchronize the IT organization with the business to provide quality information and effective information systems, enabling and sustaining the continuous improvement and innovation processes.”* lean IT aims to improve the performance of IT processes and services.

#### **4.1.4 LEAN OFFICE**

The ultimate goal of lean is to create a culture of continuous improvement every day, on every product or service, by everyone. Lean office is the application of lean manufacturing to the administrative processes (Pestana, 2011; Ryan, 2010). A 5S is a process to ensure work areas are systematically kept clean and organized, ensuring employee safety and providing the foundation on which to build a lean office system (Kremer and Tapping, 2005).

## **4.2 BACKGROUND**

For this exploratory research, we did a survey of many public and private databases to identify relevant studies. These research studies showed different problems encountered during the use of VDC. Many organizations believe the problems of working in silos and having badly coordinated documentation will be greatly reduced through the adoption of BIM (Hamil, 2012). However, BIM is not a panacea for the fragmented building delivery processes (Gong and Lee, 2011).

The National Institute of Building Sciences (2007) defined BIM scope's under three categorizations: as a product or intelligent digital representation of data; as a collaborative process; and as a facility lifecycle management tool of well understood information exchanges, workflows, and procedures that teams use throughout the building lifecycle.

However, in order to optimize the use of BIM, it is critical that much of these data be shared between team members at different phases of the lifecycle of a facility (Beaven, 2011). Here, the interoperability issues emerge. Lack of interoperability affects the workflow in the BIM process and ultimately impacts a project's budget (McGraw-Hill, 2007). Re-entering data from BIM into another application used by the team creates

wasteful and costly duplication of effort. McGraw-Hill (2007) also reported that manually re-entering data from application to application was the biggest cost associated with interoperability. Other costs include time spent using duplicate software, time lost to document version checking, and increased time processing requests for information. A lack of interoperability hampers that exchange, leading to redundant work and a need to invest time and money in non-standard solutions that drive up project costs (McGraw-Hill, 2009).

BIM process data flows are varied and include the transfer of structured/computable, semi-structured, or nonstructured/non-computable data between computer systems (Halfawy and Froese, 2002). As such, BIM data flows do not only include sending and receiving 'semantically rich' objects, but also the sending and receiving of document-based information (Succar, 2009). The data flow can help by managing and communicating electronic product and project data among collaborating firms and by implementing and managing collaborative relationships among members of cross-disciplinary build teams that enable integrated project execution (McGraw-Hill, 2007).

The Institute for BIM in Canada (2011) concluded that the BIM environment reduces the need for different types of paper documents. They also stated that the quality of communication between stakeholders is crucial for enabling the effective use of BIM. Normally, the design team exports every object with every possible attribute from the designer models; there can be just too much data. Very large amounts of data can be overwhelming and sometimes unnecessary (Jellings, 2012). As a solution, Reddy (2011) mentioned that owners should provide specifications in the area of data standards. Data standards are very important for developing key performance indicators (KPIs) and benchmarking. Data can become very complex, and adherence to a standard simplifies the process. The National Institute of Building Sciences (2007) emphasized that information has to be added by the party, creating the model before the receiving party can see it. To avoid frustration, the team should start the project by agreeing on what information will be added to the model and when. Each party can then plan its work, knowing what and when



to provide and to expect information through the model. Such process planning will avoid duplication, enable efficiencies, and realize the benefits from BIM adoption.

VDC is an integrated approach that requires the implementation of multiple and ever-changing relationships among project stakeholders with responsibility for the Plan, Do, Check and Act steps of each VDC element, i.e., the BIM, production plans, use of Integrated Concurrent Engineering (ICE) and metrics that pertain to project and client target performance values and performance. Each of these VDC elements uses technology tools, but their use is a social process.

VDC processes include a series of decisions about specification, generation and certification of the usability of information. This process must be efficient to be effective. Once a VDC process is efficient, an organization can then think of achieving other results (product view). The aim is to deliver higher value to the customer, and we must start from the root problem. How VDC can use lean principles, and the interactions between VDC and lean Construction, are well documented (Arayici, Coates, et al., 2011; Dave et al., 2013; Enache-Pommer et al., 2010; Sacks et al., 2010b).

Notwithstanding all the efforts that have been made, the literature does not examine how lean construction can help achieve a more efficient VDC process. Lean has a focus on production, and VDC theory considers the production of information; for example to specify, create, check and use models for physical construction during fabrication as well as on the job site. The goal of lean is waste reduction, increased customer value, and continuous improvement. Just as Edwards Deming said, “It is not enough to just do your best or work hard. You must know what to work on.” VDC is more than a technology; it has something in common with IT. Both are based on a series of tools, in which the information flows and waste is intangible since it is not budgeted or measured, so it is invisible to workers, project and senior management, i.e., invisible in practice, and generally neither noticed nor managed. In a physical environment, typical waste can often be observed easily, but in a VDC environment, process waste is historically difficult to identify and eliminate. For firms to be successful in the long term, they will need to

demonstrate what value they can add and what they can do with their models (Hodges et al., 2012). Koskela (1992) defined waste as an: “*Activity that takes time, resources or space but does not add value*”. A number of questions arise: How could lean construction help to eliminate waste in VDC use? Can we integrate lean thinking perspective and VDC methodology to reduce the waste within information flows?

### **4.3 METHODOLOGY**

The research method for our study was a broad survey and an analysis that describes actual applications of VDC and lean construction as described in the literature. This analysis refers to methods that focus on contrasting and combining results from different studies, in the hope of identifying patterns among study results, sources of disagreement among those results, or other interesting relationships that may come to light in the context of multiple studies (Rothman et al., 2008). Our analyses depend on the accuracy and thoroughness of the published studies we reviewed. For this paper, we attempted to gather existing studies that discussed occurrence of waste within actual implementation of VDC practices. The analytic method adopted consists of searching; coding and providing a descriptive analysis to synthesize the findings of VDC studies that were available in the databases.

#### **4.3.1 SEARCH PROCEDURES**

An extensive search of construction and related literature was initiated by manual and computer searches of two major online databases (ASCE and Science Direct), paper congress, and guidelines, which we reviewed from 2001 to present (Table 4-1). Each study was subjected to inclusion rules for aggregation. A study was included if:

- The studies were published by reputable sources.
- The studies reported types of waste within current VDC practices (focus on the information flow).

Table 4-1 Number of references to waste in projects that reported VDC use

ID	BASIC INFORMATION ON STUDIES	NO. OF WASTE REPORTED IN THE LITERATURE
1	Staub-French and Khanzode (2007)	4
2	Anderson et al. (2012)	4
3	The CRC for Construction-Innovation (2009)	3
4	Singh et al. (2011)	3
5	Al-Sadoon (2010)	2
6	Bernstein and Pittman (2004)	2
7	DesignBuild (2012)	2
8	Prather (2015)	2
9	Chobot (2011)	2
10	Madsen (2008)	1
11	Oakley (2012)	1
12	The Associated General Contractors of America (2006)	1
13	McGraw-Hill (2007)	1
14	The National Institute of Building Sciences (2007)	1
15	Arayici, Coates, et al. (2011)	1
16	Wang et al. (2012)	1
17	Autodesk (2010)	1
18	The Construction Users Roundtable (2010)	1
19	Schwegler et al. (2001)	1
20	Hartmann et al. (2007)	1
21	Fallon and Palmer (2007)	1
22	Kulahcioglu et al. (2012)	1
23	Statsbygg (2013)	1
24	Khanzode (2015)	1
25	Benson and Hartzog (2009)	1
26	Building and Construction Authority (2012)	1
27	Al-Mannai ((n.d.))	1
28	Sacks et al. (2010)	1

After the extensive search, we analyzed references to waste and classified these occurrences into eight types of waste reported in the literature. The number in parentheses corresponds to the examples in Tables 4-3 to 4-4: Non-value added processing (1), Motion (excess) (3), Inventory (excess) (5), Waiting (7), Overproduction (6), Employee

knowledge (unused) (2), Transportation/Navigation (8), and Defects (10). In the twenty-eight papers we analyzed, we found forty-three references to waste in the implementation of VDC (Due to space only ten references to waste are mentioned in this study). The full list of interactions of Table 4-3 to 4-4 can be accessed at: Mandujano (2015).

Figure 4-3 shows the frequency of references to waste in cases documented in the selected literature. The Pareto chart shows that only five types of waste represent 80% of the references, which suggests that if teams use lean methods and focus on elimination of these types of waste (non-value added processing, motion (excess), inventory (excess), waiting and overproduction), they can improve VDC practices dramatically.

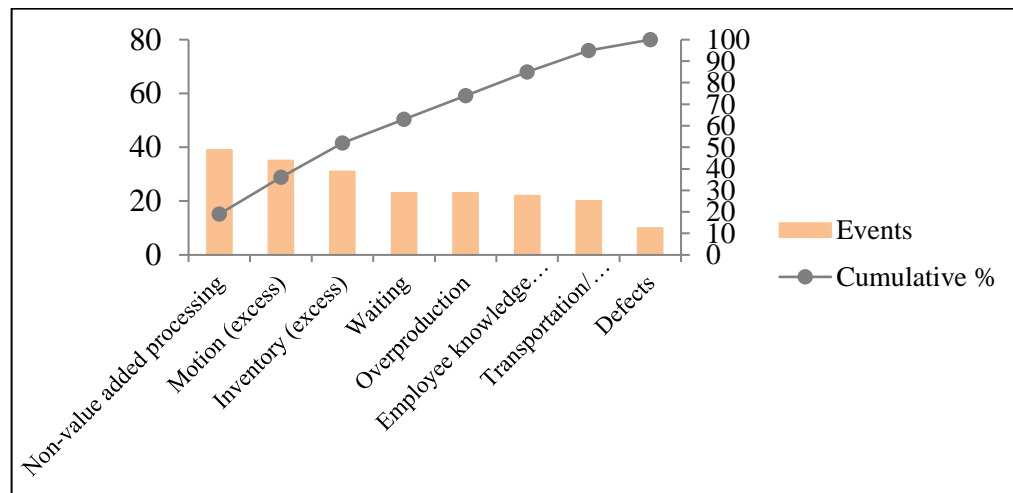


Figure 4-3 Pareto Chart about VDC waste

#### 4.4 KEYS TO A SUCCESSFUL VDC WASTE REDUCTION PROCESS

Developing an effective waste reduction process for VDC implementation is an important task before thinking about the final project results.

An example is a study conducted by Freire and Alarcón (2002); based on principles of lean production, they proposed an improvement methodology for the design process in

construction projects. The authors concluded that the methodology resulted in improvements, not only for the efficiency and effectiveness of the internal engineering products, but also for the whole project. Table 4-2 summarizes recommendations to reduce these kinds of waste within the VDC information flow (Kremer and Tapping, 2005; Pestana, 2011; Ryan, 2010).

Table 4-2 Reducing waste within the VDC information flow using lean methods

<b>TYPES OF WASTE FOUND IN THE LITERATURE</b>	<b>HOW LEAN CAN HELP TO REDUCE THIS WASTE</b>
<b>Non-value added processing</b>	<ul style="list-style-type: none"> <li>• Use an A3 report for summarizing problem-solving and status reports.</li> <li>• Use set based design.</li> <li>• Delay decisions until last responsible moment.</li> </ul>
<b>Motion (excess)</b>	<ul style="list-style-type: none"> <li>• Define the scope of the models.</li> <li>• Develop an agile process to anticipate to customer needs (customers can be internal, external, direct or indirect).</li> </ul>
<b>Inventory (excess)</b>	Gathering people and/or processes in order to improve workflow (cellular manufacturing): <ul style="list-style-type: none"> <li>• Protocols for sharing models.</li> <li>• BIM libraries.</li> <li>• Meeting and quality protocols.</li> </ul>
<b>Waiting</b>	<ul style="list-style-type: none"> <li>• Development of a communication plan.</li> </ul>
<b>Overproduction</b>	<ul style="list-style-type: none"> <li>• Use Value-Stream Mapping (VSM).</li> </ul>
<b>Employee knowledge (unused)</b>	<ul style="list-style-type: none"> <li>• Promote normalized coaching and mentoring skills, rotations, strategic tasks and competency assessments.</li> <li>• Create mechanisms to capture, communicate and apply experience-generated learning and checklists (lessons learned).</li> </ul>
<b>Transportation/Navigation</b>	<ul style="list-style-type: none"> <li>• Develop 5S plans.</li> </ul>
<b>Defects</b>	<ul style="list-style-type: none"> <li>• Use simple, grass-roots level suggestions to eliminate waste.</li> </ul>

## 4.5 DISCUSSION

Although studies have been performed about the connection between VDC and lean construction (Arayici, Kiviniemi, et al., 2011; Dave et al., 2013; Enache-Pommer et al., 2010; Sacks et al., 2010b), this article reports and discusses a part of VDC practices that has not been systematically studied: waste within the implementation of VDC. Our literature survey finds many references to waste in the VDC literature, which suggests that the waste exists in current practice. We suggest that current practice is a root cause of the waste problem, and lean methods can help to address that problem. We suggest that it is crucial for the AEC industry to think seriously about the methods of VDC implementation, specifically to focus on the method and not on a specific technology. The application of VDC can build on a Plan-Do-Check-Act cycle (Tague, 2005) in which the Plan steps are defined as lean-based production plans and the Check steps are lean-inspired checks that the work done in the Do step aligns with the planned specification. Examples of the Check step include quality conformance of BIMs and installed work, cost conformance to daily and milestone budgets and schedule conformance, or Planned Percent Complete (PPC). A company should empower stakeholders to formalize the process of VDC and then later automate all tasks.

This exploratory literature suggests that VDC practice is informal and frequently include waste as viewed from a lean Thinking perspective. VDC practitioners may benefit from careful attention to their VDC management processes to reduce waste.

Furthermore, profitability is becoming increasingly difficult to preserve, and production challenges directly impact margins (Shurling, 2013). VDC is an initiative that offers huge potential benefits to the AEC industry. Information flows throughout all VDC processes, and these processes must be efficient in order to achieve better results. It is unwise to think of lean construction only at the production phase or as an initiative that

helps VDC to achieve better results. Lean Thinking can go through every single phase of VDC methodology. It allows the specification of how to carry out a process, and VDC ensures that processes work consistently. Lean Thinking can take VDC to the next level.

#### **4.6 SUMMARY AND CONCLUSIONS**

This exploratory research found reported occurrence of waste in current VDC practices. We suggested there are big opportunities for project teams to introduce lean methods in VDC practice, with the goal to reduce waste and create a more efficient VDC processes. The synergy between lean construction and VDC is not new. Investigations concur on the potential that is achieved by implementing both initiatives (Dubler et al., 2010; Sacks et al., 2010; Tague, 2005). Furthermore, VDC provides the means and methods to implement lean principles and incorporate management principles that help to eliminate waste, reduce costs, improve productivity, and create positive results for projects. Eighty percent of the literature references reported five types of waste, suggesting that if project teams focus on eliminating those five types, they can improve VDC practices dramatically. The five types of waste most mentioned in our literature survey are:

- Non-value added processing,
- Motion (excess),
- Inventory (excess),
- Waiting and
- Overproduction

Many lean methods are available to help the AEC industry to reduce waste in its VDC implementation. For example, using set-based design can help to reduce the non-value-added processing. Value-Stream Mapping (VSM), a method to analyze every step involved in the material and information flows needed to bring a product from order to delivery, can be an option to reduce overproduction. Moreover, gathering people and/or processes in

order to improve workflow e.g. protocols for sharing models, BIM libraries, meeting protocols, and quality protocols can help to reduce excess inventory and to develop Knowledge Management Strategies (Arriagada and Alarcon, 2013).

The literature survey suggests that VDC practice is informal and VDC practitioners may benefit from careful attention to their VDC management processes to reduce waste. If lean principles, systems and tools are applied through every single phase of VDC practice the AEC industry can take better advantage of both powerful approaches to design and construction. The results presented in this paper are part of an ongoing research project on VDC implementation strategies, future research will further explore VDC implementation approaches using the lean thinking perspective.

Table 4-3 Evidence of waste in VDC Practice

	EVIDENCE FROM ACTUAL PRACTICE AND/OR RESEARCH	Defects	Overproduction	Waiting	Non-value added processing	Transportation	Inventory (excess)	Motion (excess)	Employee knowledge (unused)
1	What usually happens within projects is that specialists create redundant and inconsistent documents, so time is wasted (Madsen, 2008).			•	•	•		•	
2	In many cases, companies spend thousands of dollars on software and BIM training, then leave the project and the investment is wasted (Oakley, 2012).						•	•	•
3	The amount of redundant effort required developing and maintaining the various databases of the specialist that employ BIM represents the greatest source of waste and error associated with BIM implementation (The Associated General Contractors of America, 2006).		•		•		•	•	
4	Interoperability issues are gaining a lot of attention with the progressive use of BIM. Re-entering from BIM into another application or platform can be a costly and wasteful duplication (Al-Sadoon, 2010).				•		•		•
5	Time spent on re-entering the data from BIM to another application is considered the main driver of additional costs. Time spent using duplicate software is ranked second in the drivers of non-interoperability. Other drivers are: time lost to document version checking, increased time processing requests for information, and money for data translators (McGraw-Hill, 2007).	•	•	•	•		•	•	
6	Since the lack of clarity in qualitative goals for BIM use can result in wasted effort, like over-detailing a model or not fully capturing data in formats useful to existing facility management systems (The National Institute of Building Sciences, 2007).	•	•		•		•	•	



Table 4-4 Evidence of waste in VDC Practice

	<b>EVIDENCE FROM ACTUAL PRACTICE AND/OR RESEARCH</b>	<b>Defects</b>	<b>Overproduction</b>	<b>Waiting</b>	<b>Non-value added processing</b>	<b>Transportation</b>	<b>Inventory (excess)</b>	<b>Motion (excess)</b>	<b>Employee knowledge (unused)</b>
7	The methods of sharing outputs and interaction with other consultants within the team were also critical (Arayici, Coates, et al., 2011).			•		•		•	•
8	Carrier mechanisms—the methods for sharing computable information between applications and processes—may become more important than the data itself (Bernstein and Pittman, 2004).				•	•	•	•	
9	Improve efficiencies of delivery. Designers and contractors should be encouraged to eliminate redundant work processes through close collaboration. Re-definition of traditional delivery roles could be required (The Construction Users Roundtable, 2010).		•		•		•		•
10	The goal is to reduce the number of redundant tasks and to bring the necessary stakeholders on board at the right time to enable the generation of project information that can be shared electronically with others in the same phase and throughout the future phases of a project (Schwegler et al., 2001).	•			•		•	•	

## **5 MODELING VIRTUAL DESIGN AND CONSTRUCTION IMPLEMENTATION STRATEGIES CONSIDERING LEAN MANAGEMENT IMPACTS**

### **5.1 INTRODUCTION**

Virtual Design and Construction (VDC) is producing major changes in the Architecture, Engineering, and Construction (AEC) industry. Kunz and Fischer (2011) define VDC as *“the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives.”* VDC models can simulate the complexity of the implementation of construction projects, help to understand the difficulties that could potentially exist among members of the project team, help to analyze risks, and deal with a virtual world before any construction work is carried out in the real world (Khanzode et al., 2006). Building Information Modeling (BIM) is an important part of VDC.

On the other hand, Lean management (we use the term Lean management instead of Lean construction to keep a broader view) is a production management-based project delivery system emphasizing the reliable and speedy delivery of value (J. Womack et al., 1990). The goal is to build a project while maximizing value, minimizing waste, and pursuing perfection for the benefit of all project stakeholders (J. P. Womack and Jones, 2010).

The literature shows important benefits of the independent and joint implementation of VDC and Lean, evidencing their strong connections and potential synergies. (Bell and Orzen, 2010; Dave et al., 2013; Hardin and McCool, 2015; Ryan, 2010; Volk et al., 2014). In fact, the literature indicates hundreds of interactions between these two approaches

(Alarcon et al., 2013; Eastman et al., 2011; Sacks et al., 2010) and suggest that stakeholders' goals are more likely to be fulfilled when these approaches are carried out together (Alarcon et al., 2013; Arayici, Coates, et al., 2011; Arayici, Kiviniemi, et al., 2011).

Despite the evidence of the synergies between VDC and Lean management, the understanding of how Lean impacts on VDC implementation is still low. VDC methods are implemented according to anecdotes and beliefs based on past projects (i.e., there are no clear implementation guidelines), which are not substantial enough for industry professionals to formalize lines of implementation and apply them throughout a project (Gao and Fischer, 2008), and they do not explicitly consider the impact of the use of Lean on the project (Sacks et al., 2010).

This study presents a performance modeling methodology that will allow architecture, engineering, and construction (AEC) companies to assess VDC implementation strategies, including Lean management as a moderator of these strategies' outcomes.

The methodology is based on a conceptual model and the PLS (Partial Least Squares) method to analyze the relations in the conceptual model. A benefit of this methodology will help organizations in the selection of VDC implementation strategies, by providing decision support capabilities based on mathematical models.

Data from a VDC survey conducted in the United States (U.S.), is used to test the modeling methodology and its analysis capabilities. It is important to mention that the survey used the abbreviation VDC/BIM referring to the use of VDC, including BIM (product), process and organization modeling. This research will use VDC for simplicity and to keep a general view.

This paper is structured as follows. In order to apply the model, section 5.2 explains the fundamentals of the mathematical method that used in this study (PLS). Section 5.3 presents the research method. Section 5.4 and 5.5 use data from a Center for Integrated Facility Engineering (CIFE) survey to design the VDC/Lean influence model. Sections 5.6 and 5.7 present the analysis of the data, and in section 5.8 the summary and the

conclusions are outlined. Finally, the limitations and further research are discussed in section 5.9.

## **5.2 PLS METHOD**

Partial Least Squares (PLS) is a method that can simultaneously test the measurement model and the structural model (Vinzi et al., 2010). The measurement model describes how each of the constructs, also called latent variables, is operationalized via the manifest variables and provides information about the validities and reliabilities of the latter. The structural model represents The relationships/ hypotheses between constructs represent the structural model. PLS aims to maximize the explained variance of the endogenous constructs. The endogenous constructs serve as dependent, or as both independent and dependent variables in a structural model (Hair et al., 2013).

The method's heart is the PLS-algorithm, which is based on the PLS path model and the indicator data available. The algorithm estimates the scores of all constructs in the model, which in turn serve for estimating all path model relationships. These scores are estimated based on ordinary least squares regressions. The path models are diagrams that connect constructs based on theory and logic to visually display the hypotheses that will be tested (Hair et al., 2013). Constructs are represented in graphical path models as circles or ovals. The indicators or manifest variables are directly measured observations and are represented in these models as rectangles (Vinzi et al., 2010). The constructs measure concepts that cannot be directly observed by means of multiple items or indicators, in most cases previously validated. The indicators are directly measured observations generally referred to as either items or manifest variables represented in path models as rectangles. They are also available data (e.g. responses to survey questions). In a Formative model, the indicators determine or cause the construct. According to MacCallum and Browne

(1993), “in many cases indicators could be viewed as causing rather than being caused by the construct measured by the indicators” (p. 117).

PLS understands the construct as weighted sums of their respective indicators and attempts to predict values for the latent variables using multiple regressions.

Particularly, PLS is used in this research because the relationship between a construct and its indicators can be modeled as formative, which is an advantage compared to the covariance-based methods. Also, PLS can be used when there is no strong existing theory, and hypotheses are derived from a macro-level theory in which all relevant variables are not known, relationships between constructs are conjectural, sample size is very large or small, and a large number of manifest and latent variables are modeled (Falk and Miller, 1992; Wold, 1980).

According to Jöreskog and Wold (1982), “*PLS is primarily intended for causal-predictive analysis in situations of high complexity but low theoretical information*” (p.270). In fact, it is possible to use mixed methods to run PLS (i.e., quantitative: survey, and qualitative: case studies). It is important to note that PLS works as long as the data have the same unit (Vinzi et al., 2010).

Another key characteristic for choosing PLS is that it can deal with moderators. Moderators are qualitative and/or quantitative variables that affect the direction and/or strength of an independent variable and a dependent variable (Baron and Kenny, 1986). After a systematic review of all these conditions and the nature of the survey-data, we chose PLS as an appropriate method for this study. In this research, all the constructs are treated as a formative. The use of formative constructs is because success factor studies should concentrate on the impact of success drivers; their indicators should be actionable and, therefore, they need to be formative (Albers, 2010). For constructs using formative measures, is necessary to look at the weights of its indicators, as they provide information about the creation/formation of the construct (Duarte and Raposo, 2010; Vinzi et al., 2010). The weight indicates the importance of the contribution of the associated latent variable. According to Hair et al. (2013), “*The outer weight is the result of multiple*

*regression with the latent variable scores as the dependent variable and the formative indicators as the independent variables. Since the construct itself is formed by its underlying formative indicators as a linear combination of the indicator scores and the outer weights, running such a multiple regression analysis yields a coefficient of determination ( $R^2$  value) of 1.0. That is, 100% of the construct is explained by the indicators”* (p. 127). The traditional methods of construct validity and reliability are not appropriate for formative constructs (Bollen and Lennox, 1991; Diamantopoulos and Winklhofer, 2001). Therefore, construct validity in terms of convergent and discriminant validity is not meaningful for formative constructs. However, in a formative measurement variable, the problem of multi-collinearity may occur, if the indicators are highly correlated to each other. Thus, we use Variance Inflation Factor (VIF) which quantifies the severity of collinearity among the indicators in a formative measurement model VIF is directly related to the tolerance value ( $VIF_i = 1/\text{tolerance}_i$ ). Values greater than 5.0 indicate a potential collinearity problem (Hair et al., 2013). PLS relies on a nonparametric bootstrap procedure to test coefficients for their significance. In bootstrapping, a large number of samples are drawn from the original sample with replacement. Replacement means that each time an observation is drawn at random from the sampling population, it is returned to the sampling population before the next observation is drawn. To test whether path coefficients differ significantly from zero, p-values were calculated using the bootstrapping procedure. Contrary to the default of 100 cases and 100 samples, we calculated the p-values with 1000 cases and 500 samples to get more stable results. Nevitt and Hancock (2001), indicated that bootstrapping tends to generate more stable resample path coefficients (and thus generate more reliable p-values) with larger samples and with samples where the data points are evenly distributed on a scatter plot. Similarly, Gould et al. (2006) suggested choosing a sample size of the bootstrapping procedure that is equal to the number of cases in the original dataset, because the standard error estimates are dependent upon the number of observations in each replication.

The standardized coefficients or beta coefficients ( $\beta$ ) are the estimates resulting from the multiple regression analyses that have been standardized so that the variances of dependent and independent variables are 1. In PLS,  $\beta$  identify the importance of each predictor in the model and correspond to the standardized X variables and standardized Y variables. The coefficient matrix (dimension  $p \times r$ , where  $p$  = number of predictors and  $r$  = number of responses) is calculated from the weights. In addition, to evaluate the model, PLS uses the coefficient of determination ( $R^2$ ) value.  $R^2$  value is a measure of the model's predictive power and is calculated as the squared correlation between a specific endogenous construct's actual and predicted values. The  $R^2$  value ranges from 0 to 1, with higher levels indicating higher levels of accuracy and a more robust model. It is difficult to provide rules of thumb for acceptable  $R^2$  value, for example:  $R^2$  values of 0.10 are considered high in success driver studies (Duarte and Raposo, 2010). Also,  $R^2$  indicates that the values of the construct in the model can be well predicted via PLS.

### 5.3 RESEARCH METHOD

Figure 5-1 depicts the main steps of the research method methodology.

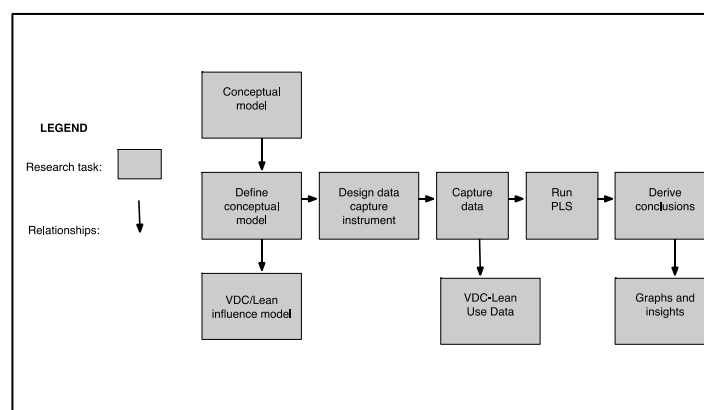


Figure 5-1 Research method.

Using a conceptual model that is proposed in Section 5-4, the users can design a VDC/Lean influence model, that captures the scope of the VDC implementation and lean use. Based on that customized conceptual model, a data capture instrument must be designed and applied. Then, the PLS method can be used on that data and the results can be analyzed and interpreted using descriptive statistics (as shown in Section 5-6). Given the time requirements to capture enough data to run PLS and to obtain interesting and valid results, we decided to use an existing set of data from a CIFE survey, provided by Stanford University, as a test for our VDC/Lean influence model and its analysis capabilities. As can be seen, we designed VDC/Lean influence model based on the existing set of data. This simplification of course affects the scope of the VDC implementation and lean use under analysis, however it does not affect its validity.

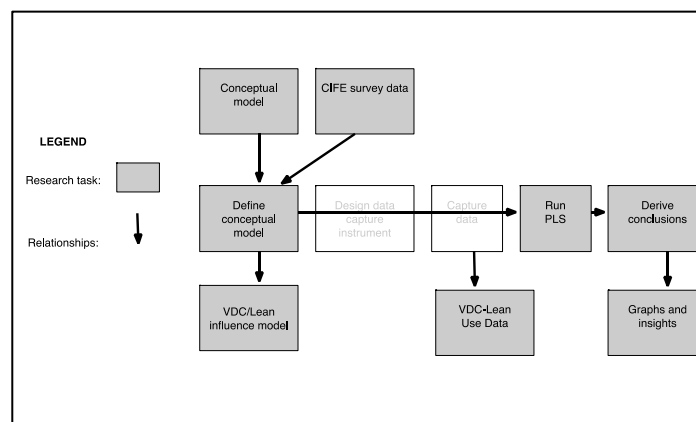


Figure 5-2 Actual research method in this study.

## 5.4 CONCEPTUAL MODEL

VDC implementation strategies are a set of decisions made by a company. In this context, VDC implementation is defined as the carrying out, execution, or practice of a plan,



method, or any design for doing something. Implementation is the action that must follow any preliminary thinking for something to happen. However, given the uncertainty of the environment, the actions taken may require some modifications to what was originally planned. The implementation processes are purposeful and are described in sufficient detail so that independent observers can detect the presence and strength of the specific set of activities related to the implementation. The designed plan of action for achieving an important goal is called a strategy. A strategy that has broad buy-in will allow one to take control of one's destiny; further, it will help secure the resources that are necessary to transform plans into reality (Cramm, 2013). VDC has a certain set of strategic components, specifically people, processes, and technology. Luftman et al. (1993) indicated that it is important to be clear on these three aspects, as they are essential to any organization. They have to be aligned with each other to attain successful results (Avison et al., 2004; Ramakrishnan and Testani, 2011). Strategies should be created in all three aspects to achieve the maximum benefit of technology (Morgan and Liker, 2006; Williams and Leask, 2011). Many case studies have concluded that the incorporation of the strategic components is crucial to achieving the maximum benefits offered by VDC (Arayici, Coates, et al., 2011; Arayici, Kiviniemi, et al., 2011; Eastman et al., 2011; Gao, 2011; Gao and Fischer, 2008; Gilligan and Kunz, 2007; Khanzode et al., 2006). While VDC aims at improving processes and eliminating waste from those processes, a review of the existing literature revealed several critical points of waste inside VDC practice from a Lean management perspective (Mandujano et al., 2016). This finding suggests big opportunities for project teams to introduce Lean management in VDC practice, with the goal to reduce waste and create a more efficient VDC processes. Mandujano et al. (2016) concluded that if teams use Lean methods and focus on elimination of these types of waste (non-value added processing, motion (excess), inventory (excess), waiting and overproduction), they can improve VDC practices dramatically. Therefore, we introduce formal consideration of Lean management and a waste perspective into the use of VDC models to make them simpler, more consistent, and less expensive. This can be achieved by a continuous cycle

of identifying points of waste, prioritizing actions for improvement, and implementing these improvements (Mandujano et al., 2016). Lean management provides efficient and standardized methods that enable this continuous improvement. To consider the integration of VDC and Lean approach, the authors use Lean management as part of the model. The Lean moderator will moderate in size and/or strength the direction and/or strength of constructs. Figure 5-3 presents the generic conceptual model of a VDC implementation. This conceptual model exhibits the variables and interactions that influence the VDC implementation in a construction company and it is a model proposed to identify how a VDC strategy impacts the company's performance. The conceptual model has four variables: (1) external factors; (2) strategic components (people, processes and, technology); (3) Lean management; and (4) performance. In the strategic component variable, each component (C) is used in different strategic alternatives (A), which join specific decisions made by a company to design each VDC implementation strategy. Then, each alternative (A) is measured by a series of indicators (i).

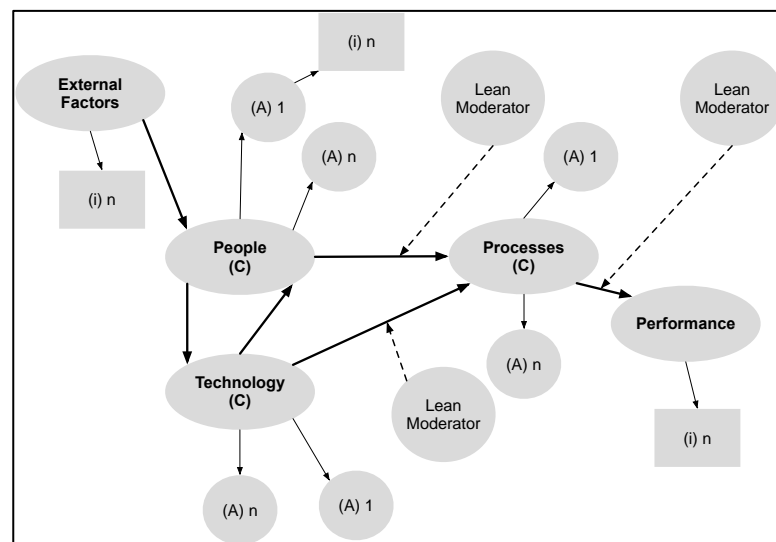


Figure 5-3 P-P-P Conceptual model (ovals are constructs and rectangles are indicators).

The paths within the model are based on previous literature (For more detail, see Mandujano (2016)). Similarly, some other indicators measure the variables of external factors, Lean management, and performance variables. The people and technology components impact the process component. This component, in turn, propagates the impact to performance. Finally, the Lean moderators impact each of the paths between the strategic components. Figure 5.4 is an example of how a Lean moderator works.

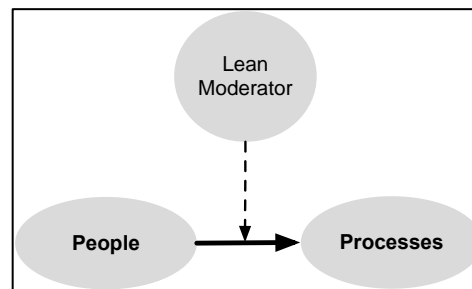


Figure 5-4 Lean moderates the effect of People on Processes.

The conceptual model then is defined as a set of variables whose effects propagate from left to right, as a complex system of interrelated and interdependent activities that affect one another. The external factors are variables whose effects propagate from the external to the internal variables.

## 5.5 VDC/LEAN INFLUENCE MODEL

As explained in section 5.3, we tested the research method with data obtained by the Center for Integrated Facility Engineering (CIFE) at Stanford University. Therefore, we generated a VDC/Lean influence model from an online survey regarding the use of VDC in the AEC industry. The survey questions are presented as constructs in Tables 5-1 through 5-6. These tables include the minimum and maximum values for each construct and the

respective weights. The weights result from running the PLS-algorithm using the CIFE data. In the following paragraphs, we describe the steps to customize the conceptual model: the survey data, the hypotheses that were tested and the results of the analysis.

The data from the CIFE survey were collected in 2007 and contained answers from 178 respondents representing a broad mix of geographic locations, business sizes, technical disciplines, and project types. The respondents mainly operated throughout the Northeast to Pacific Coast in the U.S. The companies provided services in multiple phases such as pre-project planning, architecture, engineering, construction, construction management, structural steel design, mechanical, electrical, and plumbing services (MEP) and own facilities. The projects costs go from < \$500K to > \$1B. The types of the projects are multi-family housing, small and large office, mid and high raise, power/process plant, and heavy civil, e.g., highway. The questions ranged from those related to general information to those designed to explore the performance obtained through VDC. Using the CIFE survey as a starting point, the different variables for the conceptual model of VDC implementation were created.

The description and definitions of the VDC/Lean influence model variables are based on the literature. Figure 5-5 presents the VDC/Lean influence model. Each question of the survey was related to a variable: Strategic Components (People, Processes, and Technology), External Factor, Performance, and Lean management as a moderator. The Strategic Components are composed by a set of Alternatives. The variable previously validated that best adapted to the survey data were proposed by Duy Nguyen et al. (2004) and Garbharran et al. (2013) with each question retrofitted in these constructs. Tables 5-1, 5-2, and 5-3 show the indicators that measured each alternative.

The Strategic Components are defined as follows:

*People:* People who are capable of supporting staff and/or executing the process of implementing VDC. Within the people construct we defined the following variables:

- *Commitment*: This variable was used to measure the willingness of all parties involved in managing, planning, designing, and operating VDC implementation.
- *Comfort*: The use of this variable was to ensure that all the resources, efforts, and leadership were well aligned to carry out the VDC implementation.
- *Communication*: This measure helped clarify and disseminate all necessary information related to VDC implementation across all participants.

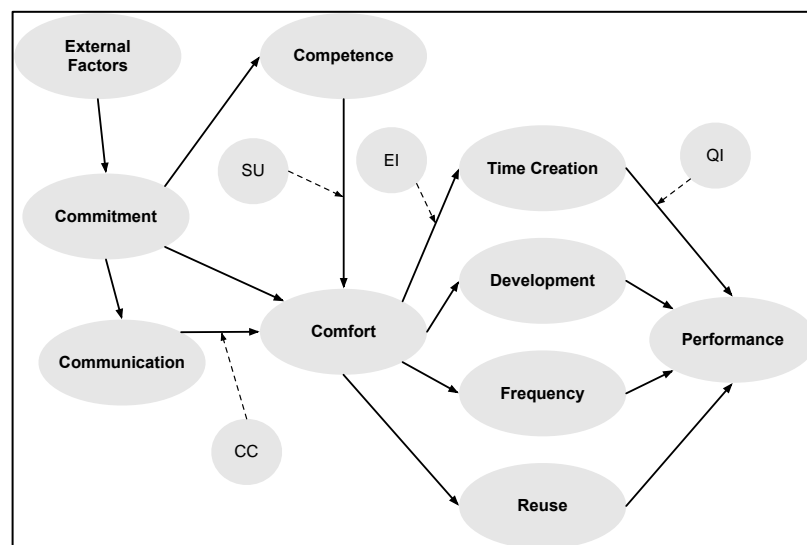


Figure 5-5 VDC/Lean influence model (C-C-C model).

*Processes*: Operational implementation plans that allow project members to monitor, control, and achieve VDC implementation. Within the processes construct we defined the following variables:

- *Development*: This variable was used to identify the phase of the project in which developing the VDC methodology was emphasized.
- *Frequency*: Measures the degree of automation of information flows between different models.

- *Time Creation:* Measures the phase of the project in which creating or updating VDC models was emphasized.
- *Reuse/ recreation:* Measures the degree of automation of information flows between different models.

Table 5-1 PLS estimated indicator weights for people construct. As part of the data analysis method, I converted text answers to survey questions to Likert scale values in the range MINIMUM to MAXIMUM as shown in the table. The PLS method calculated the significance of each variable in the set of variable types, shown in the WEIGHTS column.

COMMITMENT	MINIMUM	MAXIMUM	WEIGHTS
Management support was significant in deriving value from use of VDC methods for your project.	0	1	0.14
Participant management was significant in deriving value from use of VDC methods for your project.	0	1	0.14
Direct cost for VDC modeling and analysis software, support hardware for your project (K\$):	0	4	0.30
In the past 12 months, how many projects used Visualization Phase Virtual Design and Construction (VDC) methods?	0	5	0.31
In the past 12 months, how many projects used Prediction, Integration or Automation (beyond Visualization) Phase Virtual Design and Construction (VDC) methods?	0	5	0.31
<b>Adj. R-square</b>			<b>0.01</b>
<b>AVE</b>			<b>0.60</b>
<b>VIF</b>			<b>4.26</b>
COMMUNICATION	MINIMUM	MAXIMUM	WEIGHTS
Do you track the specific quantitative impacts of VDC use on this project's schedule?	0	2	0.67
For the questions above regarding cost, what is the source of the information on which you base your estimate?	0	5	0.67
<b>Adj. R-square</b>			<b>0.27</b>
<b>AVE</b>			<b>0.54</b>
<b>VIF</b>			<b>1.69</b>
COMFORT	MINIMUM	MAXIMUM	WEIGHTS
Average total Full Time Equivalent (FTE)-hours/week (last year) using VDC methods of your company staff on your project	0	5	0.34
Availability of staff was significant in deriving value from use of VDC methods for your projects.	0	1	0.46
Contractual/Regulatory environment was significant in deriving value from use of VDC methods for your projects.	0	1	0.45
<b>Adj. R-square</b>			<b>0.48</b>
<b>AVE</b>			<b>0.61</b>
<b>VIF</b>			<b>3.22</b>

*Technology:* The infrastructure used to communicate, support, and make the most efficient implementation of VDC properties. Within the technology construct we defined the following variables:

- *Competence:* This variable was a measure to ensure that all the parties have the technology and experience required to undertake VDC implementation.

Table 5-2 PLS estimated indicator weights for processes construct. As part of the data analysis method, I converted text answers to survey questions to Likert scale values in the range MINIMUM to MAXIMUM as shown in the table. The PLS method calculated the significance of each variable in the set of variable types, shown in the WEIGHTS column.

<b>DEVELOPMENT</b>	<b>MINIMUM</b>	<b>MAXIMUM</b>	<b>WEIGHTS</b>
Pre-project planning was the area we placed significant attention for developing VDC capabilities.	0	1	0.21
Support conceptual design was the area we placed significant attention for developing VDC capabilities.	0	1	0.28
Support design definition was the area we placed significant attention for developing VDC capabilities.	0	1	0.31
Support construction document development was the area we placed significant attention for developing VDC capabilities.	0	1	0.31
Support field construction management was the area we placed significant attention for developing VDC capabilities.	0	1	0.29
Support operations and maintenance was the area we placed significant attention for developing VDC capabilities.	0	1	0.05
<b>Adj. R-square</b>			<b>0.29</b>
<b>AVE</b>			<b>0.40</b>
<b>VIF</b>			<b>1.57</b>
<b>TIME CREATION</b>	<b>MINIMUM</b>	<b>MAXIMUM</b>	<b>WEIGHTS</b>
Pre-project planning was the area we created or updated VDC models.	0	1	0.20
Conceptual design was the area we created or updated VDC models.	0	1	0.18
Schematic design was the area we created or updated VDC models.	0	1	0.22
Design definition was the area we created or updated VDC models.	0	1	0.22
Construction documents was the area we created or updated VDC models.	0	1	0.21
Field construction management was the area we created or updated VDC models.	0	1	0.21
Operations and maintenance was the area we created or updated VDC models.	0	1	0.19
<b>Adj. R-square</b>			<b>0.21</b>
<b>AVE</b>			<b>0.46</b>
<b>VIF</b>			<b>1.87</b>
<b>FREQUENCY</b>	<b>MINIMUM</b>	<b>MAXIMUM</b>	<b>WEIGHTS</b>
Build and update models by co-located project staff - FTE Hours / Week.	0	6	0.27
Build and update models by remote shared corporate staff - FTE Hours / Week.	0	6	0.37
Preconstruction analysis, e.g. clash detection, costing, or work sequencing - FTE Hours / Week.	0	6	0.35
Informational updating for personnel outside the project team - FTE Hours / Week.	0	6	0.27
Marketing for actual or prospective clients - FTE Hours / Week.	0	6	0.35
<b>Adj. R-square</b>			<b>0.16</b>
<b>AVE</b>			<b>0.36</b>
<b>VIF</b>			<b>1.40</b>
<b>REUSE</b>	<b>MINIMUM</b>	<b>MAXIMUM</b>	<b>WEIGHTS</b>
Shared VDC models with >=2 CAD packages.	0	1	0.26
Exported architectural CAD to engineering analysis tool, such as energy, lighting or structures	0	1	0.29
Created new CAD models to support engineering analysis, such as energy, lighting or structures	0	1	0.29
Manually created 3D model from 2D drawings.	0	1	0.32
Automatically generated 2D drawings from 3D models	0	1	0.31
<b>Adj. R-square</b>			<b>0.13</b>
<b>AVE</b>			<b>0.44</b>
<b>VIF</b>			<b>1.36</b>

Table 5-3 PLS estimated indicator weights for technology construct. As part of the data analysis method, I converted text answers to survey questions to Likert scale values in the range MINIMUM to MAXIMUM as shown in the table. The PLS method calculated the significance of each variable in the set of variable types, shown in the WEIGHTS column.

COMPETENCE	MINIMUM	MAXIMUM	WEIGHTS
Software/hardware were significant in deriving value from the use of VDC methods for your projects.	0	1	0.61
Average total Full Time Equivalent (FTE)-hours/week (last year) training your company staff members who are now on your project in use of VDC methods.	0	1	0.61
Adj. R-square	0	1	0.10
AVE			0.66
VIF			1.50

The *External Factors* are environmental variables that impact the implementation of the model internal variables. The external factors condition any action and represent influences of environmental features. Table 5-4 shows the indicators that measured the external factors.

*Performance Outcomes* are performance measures of interest for the companies and researchers. The outcomes are useful to reflect the impact of strategies on the company performance. The indicators that measured performance are summarized in Table 5-5.

Table 5-4 PLS estimated indicator weights for external factor constructs. As part of the data analysis method, I converted text answers to survey questions to Likert scale values in the range MINIMUM to MAXIMUM as shown in the table. The PLS method calculated the significance of each variable in the set of variable types, shown in the WEIGHTS column.

EXTERNAL FACTORS		MINIMUM	MAXIMUM	WEIGHTS
Why aren't you using VDC?	Have not had the needs / owners are not requesting it is a reason for not using VDC.	0	1	0.06
	Non- familiarity with the technology is a reason for not using VDC.	0	1	0.07
	Cost of technology / software is a reason for not using VDC.	0	1	0.06
	Lack of technical expertise is a reason of a reason of not using VDC.	0	1	0.08
	Other (please specify) reasons.	0	1	0.07
What would cause you to start using VDC?	Owner request cause us to start using VDC.	0	1	0.05
	Competitors using is a cause to start using VDC.	0	1	0.07



	Efficiency / process improvement is a cause to start using VDC.	0	1	0.06
	Other (please specify) causes to start using VDC.	0	1	0.07
Which of these factors does your organization find significant in impeding value from use of VDC methods?	Software/hardware is a factor our organization find significant in IMPEDING value from use of VDC methods?	0	1	0.00
	Training is a factor our organization find significant in IMPEDING value from use of VDC methods?	0	1	0.06
	Participant engagement is a factor our organization find significant in IMPEDING value from use of VDC methods?	0	1	0.06
	Process to identify project risks early is a factor our organization find significant in IMPEDING value from use of VDC methods?	0	1	0.07
	Process for stakeholders to interact is a factor our organization find significant in IMPEDING value from use of VDC methods?	0	1	0.07
	Contractual/regulatory environment is a factor our organization find significant in IMPEDING value from use of VDC methods?	0	1	0.07
	Management support is a factor our organization find significant in IMPEDING value from use of VDC methods?	0	1	0.07
	Availability of staff is a factor our organization find significant in IMPEDING value from use of VDC methods?	0	1	0.06
	Other factors.	0	1	0.08
What contract, legal or regulatory incentives/constraints were applied regarding use of VDC methods on this project?	Data/model sharing required constraints were applied regarding the use of VDC methods on this project?	0	1	0.03
	Data/model sharing prohibited constraints were applied regarding the use of VDC methods on this project?	0	1	0.06
	Contract provisions facilitate sharing data and models constraints were applied regarding the use of VDC methods on this project?	0	1	0.06
	Contract provisions impede sharing data and models constraints were applied regarding the use of VDC methods on this project?	0	1	0.07
	Financial provisions support modeling by my organization constraints were applied regarding the use of VDC methods on this project?	0	1	0.06
	Financial provisions impede modeling by my organization constraints were applied regarding the use of VDC methods on this project?	0	1	0.07
	N/A	0	1	0.07
	Do not know	0	1	0.07
	<b>Adj. R-square</b>	0	1	
	<b>AVE</b>	0	1	<b>0.31</b>
	<b>VIF</b>	0	1	<b>1.17</b>

Table 5-5 PLS estimated indicator weights for performance factor constructs. As part of the data analysis method, I converted text answers to survey questions to Likert scale values in the range MINIMUM to MAXIMUM as shown in the table. The PLS method calculated the significance of each variable in the set of variable types, shown in the WEIGHTS column.

PERFORMANCE	MINIMUM	MAXIMUM	WEIGHTS
How much better was average MONTHLY project COST conformance to plan in comparison with similar projects that did not use VDC (%):	0	6	0.06
How much better was FINAL project COST conformance to plan in comparison with similar projects that did not use VDC (%):	0	6	0.11
Change in project unbudgeted change orders for owner in comparison with similar projects that did not use VDC (\$M):	0	7	0.30
How much better was average WEEKLY SCHEDULE conformance (i.e., fraction of task start and finish milestones within say 2 days of planned milestone date) to plan in comparison with similar projects that did not use VDC:	0	6	0.32
How much better was FINAL project SCHEDULE conformance to plan in	0	7	0.31

comparison with similar projects that did not use VDC (%):			
Change in response LATENCY during design and or construction compared to similar projects that did not use VDC? Latency applies both to formal Requests for Information and informal questions to project co-workers.	0	6	0.24
<b>Adj. R-square</b>			<b>0.09</b>
<b>AVE</b>			<b>0.44</b>
<b>VIF</b>			<b>3.54</b>

Due to the scarcity of information regarding paths, between Lean moderators and the constructs, a search was conducted in articles focused on the factors leading to the success of construction projects and case studies of some case studies related to the use of VDC (Arayici, Coates, et al., 2011; Arayici, Kiviniemi, et al., 2011; Eastman et al., 2011; Gao, 2011; Gao and Fischer, 2008; Gilligan and Kunz, 2007; Khanzode et al., 2006). We used variables previously validated as the source of the indicators of Lean moderators (Al-Tahat and Jalham, 2013; Bell and Orzen, 2010). The Lean moderators and the paths between them were based on the ones mentioned by Fullerton and Wempe (2009) but the paths were adapted to the needs of our conceptual model. Each of the Lean moderators was placed on the critical points of waste mentioned by Mandujano et al. (2016). The moderators identified for VDC are defined as follows:

- Employee Involvement (EI): a measure of the decisions made by the staff to solve the various problems encountered in the VDC implementation.
- Quality Improvement (QI): a measure of the actions focused on increasing the quality in the process of VDC implementation.
- Setup Time Reduction (SU): a measure of the actions aimed to reduce the time taken to implement VDC.
- Cellular Construction (CC): indicates the persons/processes that are grouped to improve workflow.

Table 5-6 shows the indicators that measured each moderator based on Garbharran et al. (2013).

Table 5-6 PLS estimated indicator weights for lean moderators constructs. As part of the data analysis method, I converted text answers to survey questions to Likert scale values in the range MINIMUM to MAXIMUM as shown in the table. The PLS method calculated the significance of each variable in the set of variable types, shown in the WEIGHTS column.

<b>EMPLOYEE INVOLVEMENT</b>	<b>MINIMUM</b>	<b>MAXIMUM</b>	<b>WEIGHTS</b>
Lessons Learned	0	1	0.25
Promoting the reuse and sharing of standards, programs, modules etc.	0	1	0.25
Start with a more experienced team to help resolve the various conflicts	0	1	0.24
Communication Channels	0	1	0.25
Kanban Boards (conflict resolution)	0	1	0.26
Electronic forms a concise page (eg Toyota A3) in and maintain detailed data for a backup job.	0	1	0.23
<b>Adj. R-square</b>			<b>0.82</b>
<b>AVE</b>			<b>0.43</b>
<b>VIF</b>			<b>2.13</b>
<b>SETUP TIME REDUCTION</b>	<b>MINIMUM</b>	<b>MAXIMUM</b>	<b>WEIGHTS</b>
Model scope.	0	1	0.26
Develop an agile process to anticipate and adapt to customer needs.	0	1	0.27
Development of a communication plan with customers (external/internal).	0	1	0.28
Plan to act "proactively" to the unexpected (risk).	0	1	0.30
Promote standardized with careful coaching and mentoring skills, rotations, strategic tasks and competency assessments.	0	1	0.34
<b>Adj. R-square</b>			<b>0.19</b>
<b>AVE</b>			<b>0.45</b>
<b>VIF</b>			<b>2.09</b>
<b>CELLULAR CONSTRUCTION</b>	<b>MINIMUM</b>	<b>MAXIMUM</b>	<b>WEIGHTS</b>
Quality protocols	0	1	0.32
Protocols for sharing models	0	1	0.33
VDC libraries	0	1	0.36
Meeting Protocols	0	1	0.34
<b>Adj. R-square</b>			<b>0.16</b>
<b>AVE</b>			<b>0.53</b>
<b>VIF</b>			<b>1.55</b>
<b>QUALITY IMPROVEMENT</b>	<b>MINIMUM</b>	<b>MAXIMUM</b>	<b>WEIGHTS</b>
Create mechanisms to capture, communicate and apply experience-generated learning and checklists.	0	1	0.34
Previous indicators to measuring an action before (poke yoke) occurring residues.	0	1	0.36
Metric approach to provide customer value not profits.	0	1	0.33
Using structured measures to motivate the right behavior.	0	1	0.34
<b>Adj. R-square</b>			<b>0.27</b>
<b>AVE</b>			<b>0.52</b>
<b>VIF</b>			<b>1.85</b>

## 5.6 ANALYSIS OF THE DATA

In this research we first explore the data using descriptive statistics to understand the current scenario related to VDC in the AEC companies (Subsection 5.6.1). Further, PLS is

deployed for testing and estimating causal relationships among variables (Subsection 5.6.2).

### **5.6.1 PERFORMANCE OF COMPANIES**

We used the following six questions to compare the improvement that a company observes with and without VDC.

1. Average monthly project cost conformance to plan;
2. Final project cost conformed to planned costs;
3. Change in project (unbudgeted changes, changes requested by owner, etc.).
4. Average weekly schedule conformance (i.e. fraction of task start and finish milestones within 2 days of planned milestone date);
5. Final project schedule conformance to plan in comparison with similar projects that did not use VDC.
6. Change in response latency during design and/or construction compared to similar projects that did not use VDC.

The performance score is calculated by specifying these six items as a formative variable and then calculating the factor score. We next divide the companies into three based on their performance score. We sort the companies from low performance score to high performance, and classify the bottom 33.3% companies as low performance, middle 33.3% companies as medium performance, and the other remaining companies as high performance.

### **5.6.2 VARIABLES OF VDC IMPLEMENTATION**

Next we discuss in detail the different variables that are related to the VDC implementation. We represent the percentage of companies on each of the charts. So, for example, consider Figure 6; data asked from the companies about the importance each

performance group of companies give to the indicators for commitment, competence, comfort, and communication to deriving value from the use of VDC.

The percentage of companies is calculated by looking at the total number of companies who say yes for a particular option divided by the total number of companies. For example if there are 100 medium performance companies, and out of this only 20 companies say that management support was significant in delivering value from the use of VDC capabilities, we will say that 20% of the medium performance companies considered management support significant in delivering value from the use of VDC. As we can see, high performance companies give more attention in almost all the indicators, followed by medium performance companies, and finally the low performance companies.

Figure 5-6 suggests that commitment (management support and participant management) is crucial during the VDC implementation. Table 5-1 suggests companies must support the entire VDC implementation to achieve better performance. Figure 5-6 suggests that comfort has a central place in the model, playing the role of a connector of multiple paths. Also, figure 5-6 suggests that availability of staff is essential; in fact high performance companies mentioned the variable as the most important in deriving value from the use of VDC. Table 5-7 suggests the availability of qualified staff is necessary when VDC is being implemented.

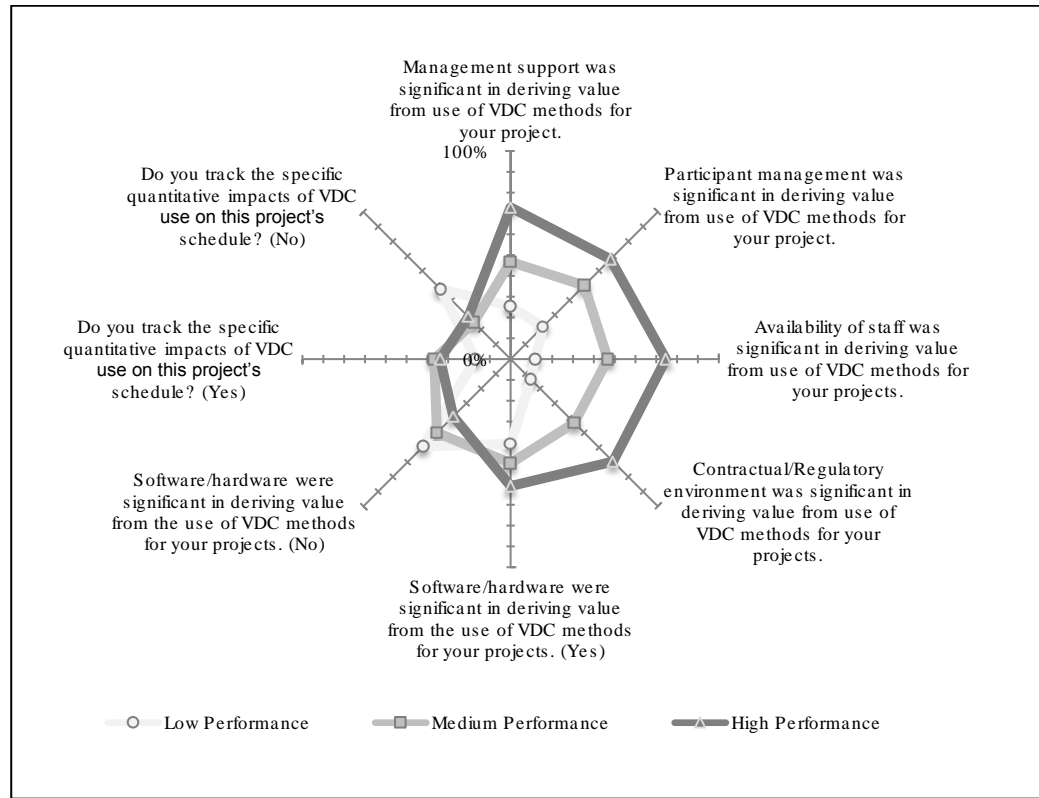


Figure 5-6 Percentage for the implementation of strategy factors

Table 5-1 suggests that people are the drivers throughout the implementation process. While VDC is a technology-based approach, people must be available to make the implementation happen; this availability, combined with a suitable, clear, and precise contractual environment, allows the “start” of the process. Figure 5-6 suggests that tracking quantitative impacts of VDC on project’s schedule was the lowest. From the results of table 5-1, we can suggest that to achieve better performance it is necessary to take into account each of the indicators of commitment, competence, comfort, and communication. One important result is that management support and the use of VDC (as a visualization prediction, integration or automation) have a strong and positive connection in the commitment construct (See table 5-1 for a more detail).

Table 5-7 PLS estimated indicator weights for external factor constructs

COMPANIES	AVERAGE OF HOURS TRAINING THEIR STAFF OF EACH PERFORMANCE GROUP OF COMPANIES.
Low Performance	5%
Medium Performance	7%
High Performance	27%

Figure 5-7 suggests that although the importance of strategy components, only half of the high companies mentioned them as a significant in deriving value of VDC.

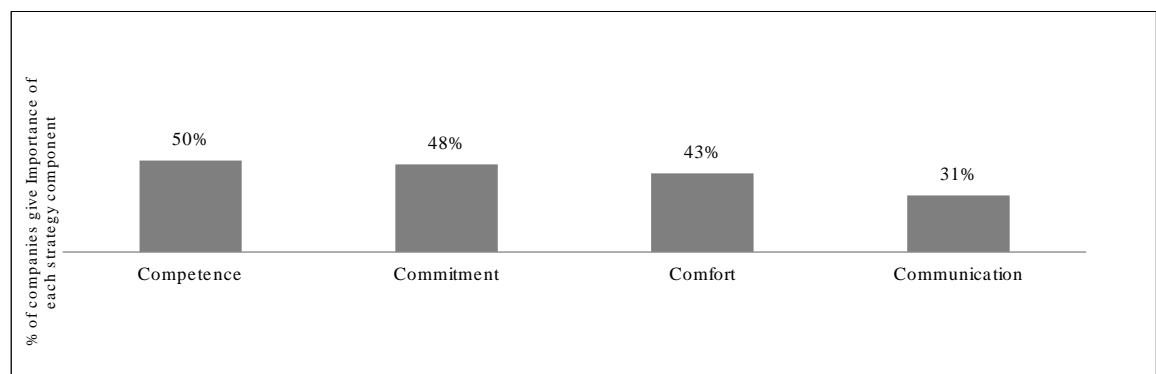


Figure 5-7 Importance of each strategy component

Figures 5-8, 5-11 and 5-13 summarize the percentage of importance each performance group of companies gives to the indicators for development, time creation, and reuse. Figure 5-8 shows that high performance companies' focus on developing VDC models in almost all the stages, followed by medium and low performance companies.

High performance companies focus on design and construction phases, followed by operation and maintenance. Specifically, high performance companies focus on support of design definition and support field construction management.

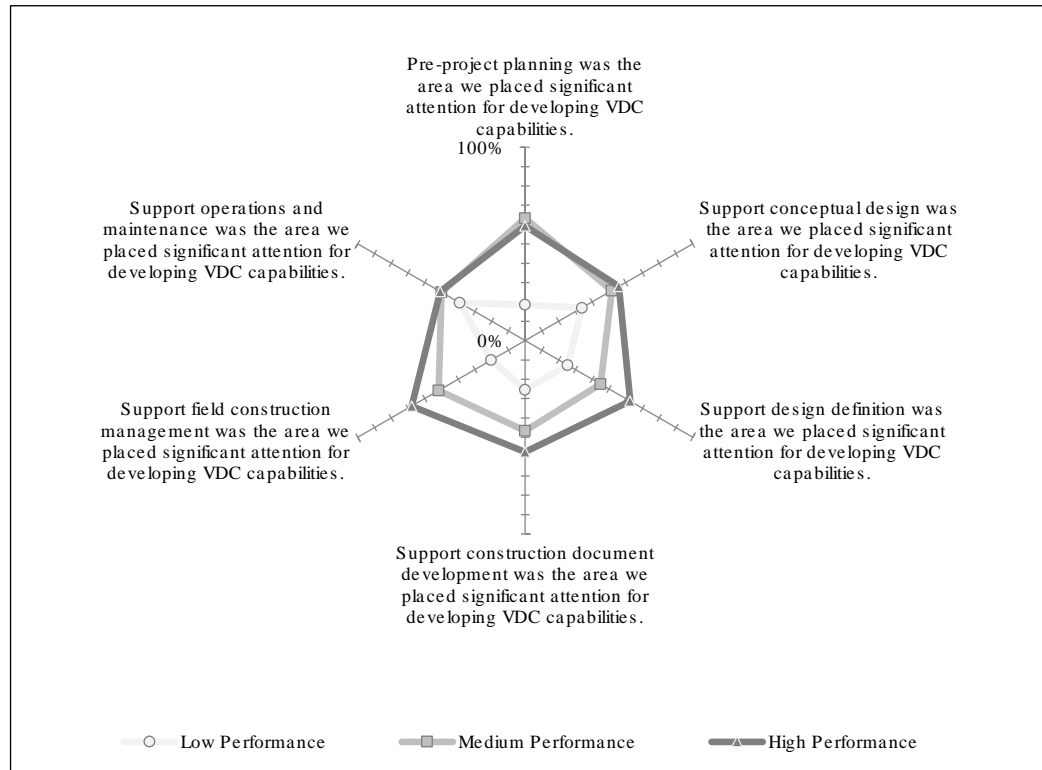


Figure 5-8 Phase in which developing VDC was emphasized

Figure 5-8 suggests that medium performance companies, as high performance companies focus in design and construction phases, but to a minor extent. With the difference that medium performance companies put a major emphasis on pre-project planning, support of conceptual design, and support of field construction management. Low performance companies emphasized the use of VDC in support of conceptual design and support of operations and maintenance. In the final stage, support operations and maintenance, the low performance companies have an increase from 20.3% to 39%, and the medium and high performance companies have a decreased, from 51.7% to 50% and 67.8% to 50.8% respectively.

From the results, we suggest that the early develop of VDC allows the design team to achieve more benefits (See Figure 5-9).



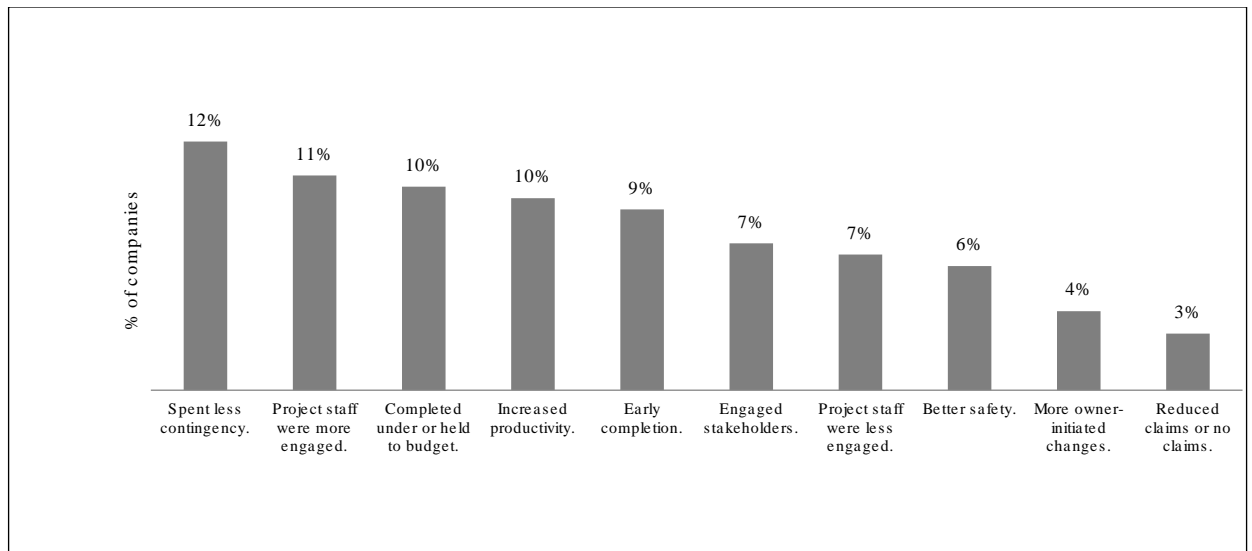


Figure 5-9 Consequences of using VDC

None of the companies (high, medium and low) was fully involved in the development of VDC through all the stages (See figure 5-10). Figure 5-9 suggests that to get the full benefits of VDC, companies need to develop VDC throughout all the phases, and not try to rescue the project in the last phase (See table 5-2).

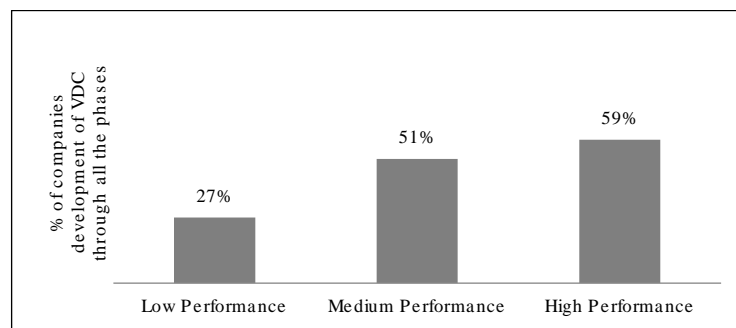


Figure 5-10 Development of VDC through all the phases

Figure 5-11 suggests that in time creation phase high performance companies have a tendency to focus on the initial phases of the project, pre-project planning and conceptual design, but without neglecting the construction (construction documents) and operation phases.

In fact, high performance companies take into account all the phases of the project in which creating or updating VDC models were emphasized. Medium performance companies focused on the conceptual design and field construction management. Last, the low performance companies put aside the initial and critical stages of all the projects (design phases) and concentrated, in a minor extent, on the construction phase.

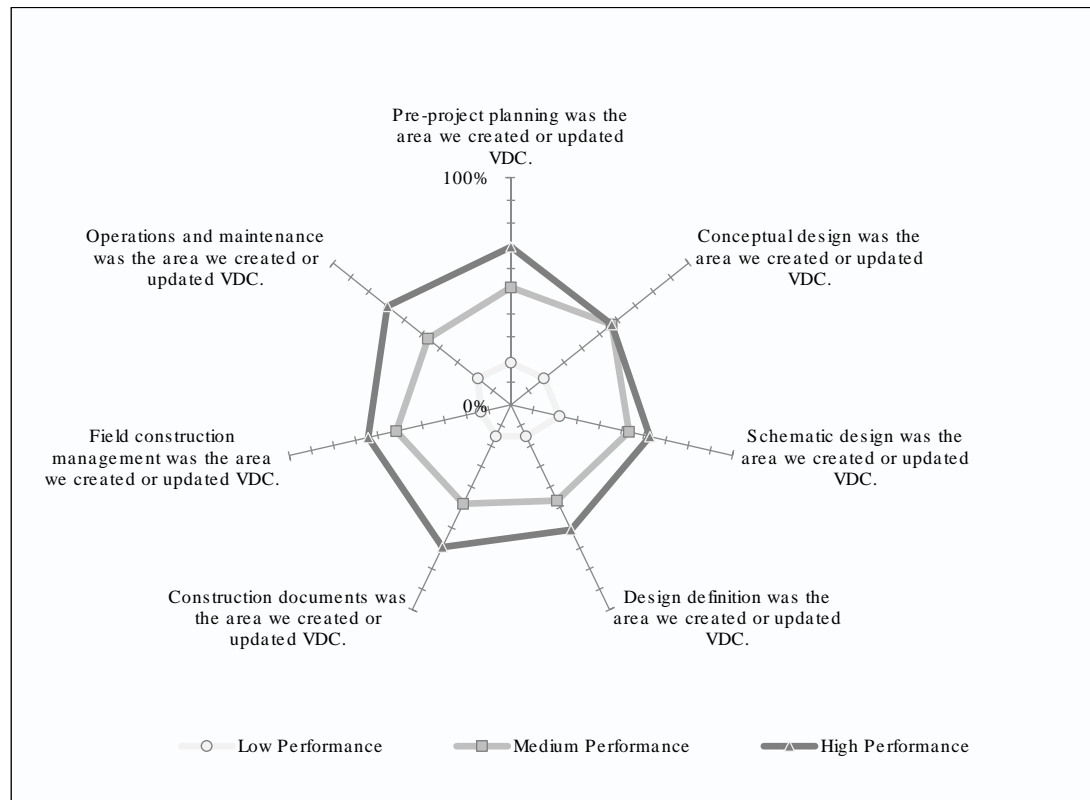


Figure 5-11 Phase which creating or updating VDC was emphasized

Although high performance companies seem to be the most apparently successful cases, their creating or updating VDC is not full at all. Figure 5-12 shows % of companies vs. performance. Only 65% of high performance companies took into account all the project phases.

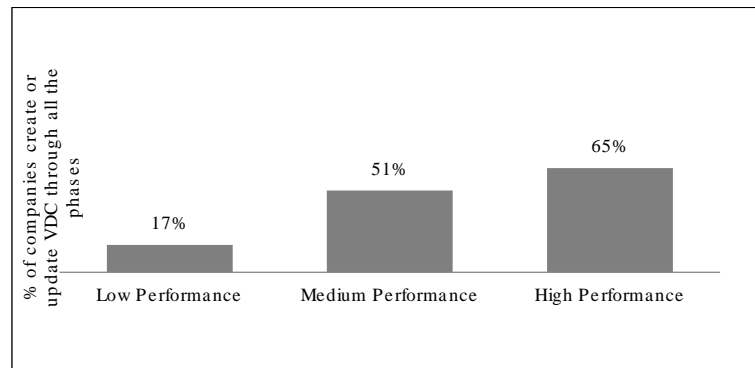


Figure 5-12 Create or update VDC through all the phases

Figure 5-13 suggests that high performance companies put a major emphasis in manually created 3D models and 2D drawings, followed by creating new CAD models to support engineering analysis, such as energy, lighting or structures. This finding represents a breakthrough in the use of VDC since first their use was in a very preliminary stage (manually created 3D models and 2D drawings), and subsequently it evolved to more complex analyses (created new CAD drawings to support engineering analysis, such as energy, lighting or structures). The medium and low performance companies had the same tendency as high performance companies but to a lesser extent, and focused on earlier project stages.

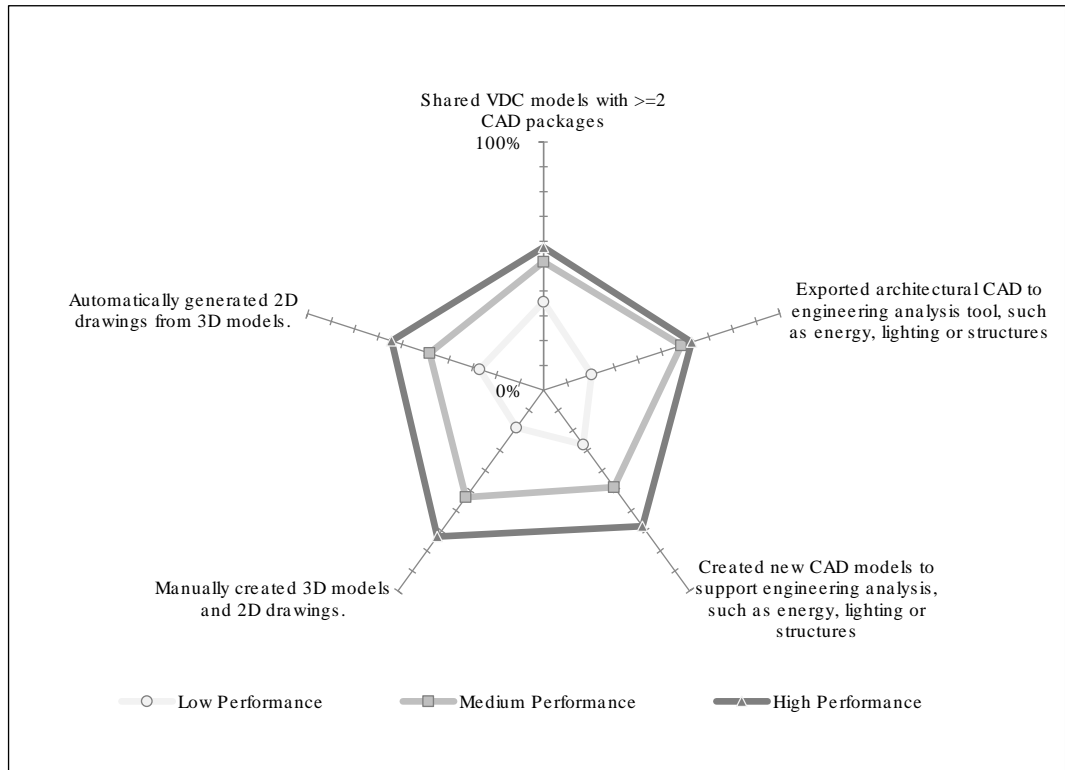


Figure 5-13 Degree of automation of information flows between different models

Although high performance companies seem to be the most apparently successful cases, their current degree of automation of information flows between different VDC models is not full at all (Figure 5-14).

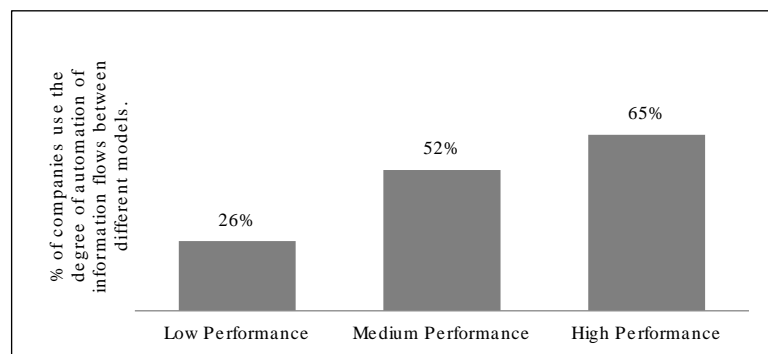


Figure 5-14 Degree of automation of information flows between different models

Figures 5-8, 5-11 and 5-13, suggest that in order to have better performance results, it is essential that companies create VDC models starting with the pre-project planning, and throughout all design phases; they should develop through the construction document development phase, focusing on the roles of building and updating models by remote shared corporate staff, and preconstruction analyses (e.g., clash detection, costing, work sequencing), and reuse the models in other roles, in addition to manually creating 3D models from 2D drawings, and automatically generating 2D drawings from 3D models. Companies should take advantage of all the potential generated by the VDC models by following these guidelines.

Moreover, we can conclude that the actual VDC implementation of projects and companies is not yet fully effective and there are many missed opportunities even in the seemingly most successful cases (See Figures 5-7, 5-10, 5-12, and 5-14).

## **5.7 LEAN IMPACT ON VDC IMPLEMENTATION**

To assess our VDC/Lean influence model, we used PLS to evaluate the relationships between the variables, and to estimate both the measurement and structural parameters. In this research, all the constructs are formative (Albers, 2010). For an overview and a discussion of the features of PLS, see Fornell and Bookstein (1982) and section 5-2 of this research. First, we present the measurement model and then the structural model.

### **5.7.1 MEASUREMENT MODEL**

The indicator weight of each item on the respective construct is summarized in Tables 5-1 to 5-6. None of the latent variables has VIF values greater than 5.0, and it can be safely concluded that there is no multicollinearity problem within any latent variable. The indicators weights for all the constructs associated with VDC implementation are also

presented in Tables 5-1 to 5-6. The results indicate that the respective indicators for each latent construct are positively and significantly related to the construct. Thus, we conclude that all measurement indicators are good predictors of their respective latent constructs.

## **5.7.2 STRUCTURAL (PATH) MODEL**

I analyzed two models in order to understand the relationship between VDC and Lean: the first VDC/Lean influence model without Lean moderators, and the second VDC/Lean influence model with Lean moderators. The model with moderators works in the same way as the one without moderators, with the difference that the moderators affect the direction and/or strength (Figure 5-5) of an independent variable and a dependent variable.

The purpose of running two models is to assess how Lean can help in a positive way in the VDC implementation processes. As mentioned before, each of the Lean moderators was placed on the critical points of waste mentioned by Mandujano et al. (2016).

### **5.7.2.1 MODEL 1. VDC/LEAN INFLUENCE MODEL WITHOUT MODERATORS**

Model 1 tested the causal relationships among different factors related to the implementation of VDC by AEC companies. All path coefficients are presented with their respective p-values in parentheses. The results of model 1 analysis indicated that the model accounted for 10.0% of the variance in Performance, 30% in Development, 14% in Reuse, 17% in Frequency, and 17% in Creation. In addition, the model also accounted for 41% of the variance in Comfort, 11% in Competence, 28% in Communication, and 2% in Commitment. As we mentioned before, Duarte and Raposo (2010) explained that the variance criterion ( $R^2$ ) for the endogenous variables must be greater than 0.1. Consistent with this, the results show that all constructs in the endogenous model are above this 0.1 rule of thumb.

The statistical results (coefficient and p-values) indicated that most paths specified in the model were positive and significant (Hair et al., 2013; Vinzi et al., 2010). The path coefficients from Frequency ( $\beta = 0.10$ ,  $p = 0.04$ ) and Creation ( $\beta = 0.21$ ,  $p < 0.001$ ) to Performance were both positive and significant, indicating that Frequency and Creation each had a significantly positive impact on Performance. The impacts of Development and Reuse on Performance were positive but statistically insignificant ( $p > 0.05$ ).

Given the exploratory nature of the study, the impacts of Development and Reuse on Performance were retained in the model. Moreover, when a model with many relationships is evaluated, factors that are individually significant may lose their power when they are evaluated together with other factors, given the interaction effects (See Esposito Vinzi et al., 2010).

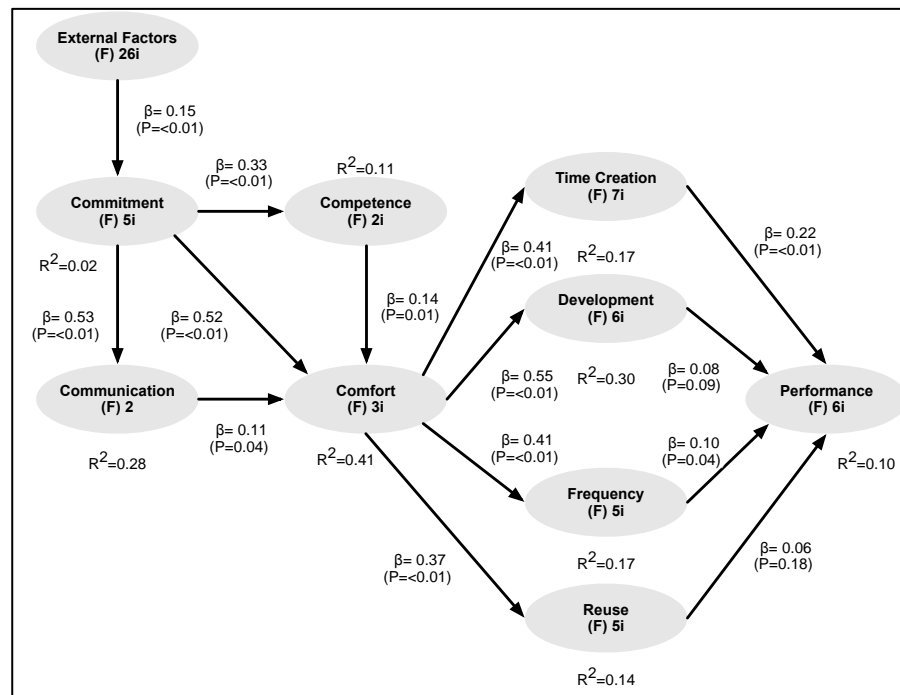


Figure 5-15 VDC/Lean Influence Model without Moderators

Comfort exerted a significant and positive impact on Development ( $\beta = 0.54$ ,  $p < 0.001$ ), Reuse ( $\beta = 0.36$ ,  $p < 0.001$ ), Frequency ( $\beta = 0.41$ ,  $p < 0.001$ ), and Creation ( $\beta = 0.41$ ,  $p < 0.001$ ). Further analysis of the model indicated that the path coefficients from Commitment ( $\beta = 0.52$ ,  $p < 0.001$ ), Competence ( $\beta = 0.13$ ,  $p < 0.001$ ), and Communication ( $\beta = 0.10$ ,  $p < 0.001$ ) to Comfort were positive and significant. Similarly, Commitment exerted a significant and positive impact on Communication ( $\beta = 0.52$ ,  $p < 0.001$ ) and Competence ( $\beta = 0.33$ ,  $p < 0.001$ ). Lastly, a significant and positive relationship between External and Commitment ( $\beta = 0.15$ ,  $p = 0.007$ ) is observed.

#### **5.7.2.2 MODEL 2. VDC/LEAN INFLUENCE MODEL WITH MODERATORS**

Moderators were introduced into model 2. With this, Lean management moderates the effect of the components inside Model 2 (See figure 5-16) and, may, influences project performance. Comparing the VDC/Lean model with and without moderators the strength of the relationships between: communication to comfort, competence to comfort, comfort to time creation and time creation to performance are all greater. The final coefficients are summarized in the following section. All coefficients are presented with p-values given in parentheses in Fig. 5-16.

The results indicated that the model accounted for 66% of the variance in Performance, 30% in Development, 14% in Reuse, 17% in Frequency, and 22% in Time Creation. In addition, the model accounted for 49.0% of the variance in Comfort, 11% in Competence, 28% in Communication, and 2% in Commitment. Statistical analysis indicated that most paths specified in the model were positive and significant. The path coefficients from Reuse ( $\beta = 0.12$ ,  $p = 0.018$ ) and Creation ( $\beta = 0.25$ ,  $p < 0.001$ ) to Performance were both positive and significant, indicating that Reuse and Creation each had a significantly positive impact on Performance. The impacts of Development and Frequency on Performance were positive but statistically insignificant ( $p > 0.05$ ).



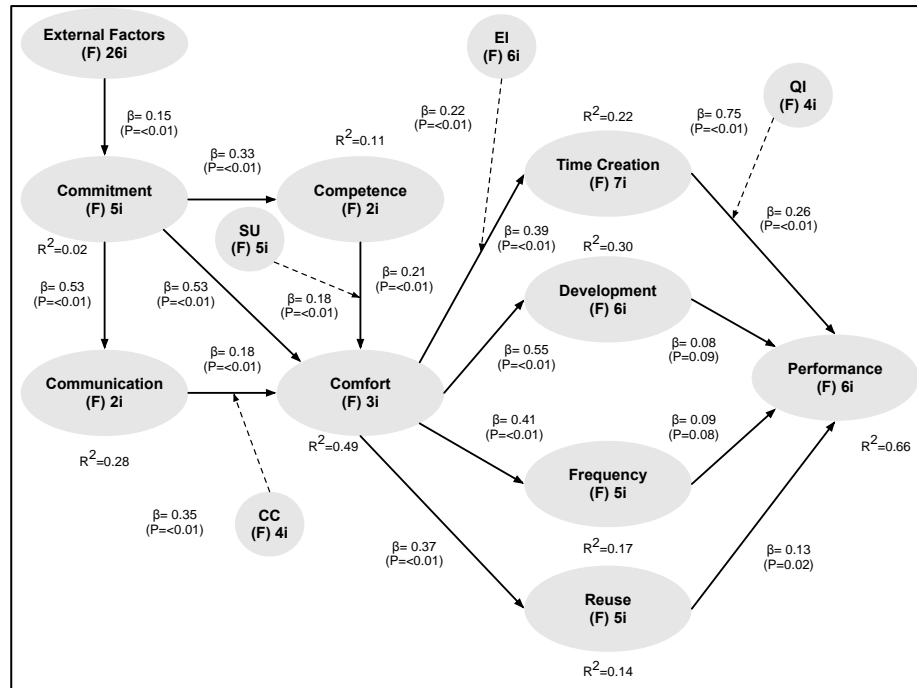


Figure 5-16 VDC/Lean influence model

Comfort exerted a significant and positive impact on Development ( $\beta = 0.54$ ,  $p < 0.001$ ), Reuse ( $\beta = 0.36$ ,  $p < 0.001$ ), Frequency ( $\beta = 0.41$ ,  $p < 0.001$ ), and Creation ( $\beta = 0.38$ ,  $p < 0.001$ ). Further analysis of the model indicated that the path coefficients from Commitment ( $\beta = 0.52$ ,  $p < 0.001$ ), Competence ( $\beta = 0.20$ ,  $p < 0.001$ ), and Communication ( $\beta = 0.18$ ,  $p < 0.001$ ) to Comfort were positive and significant.

Similarly, Commitment exerted a significantly positive impact on Communication ( $\beta = 0.52$ ,  $p < 0.001$ ) and Competence ( $\beta = 0.33$ ,  $p < 0.001$ ). Lastly, a significant and positive relationship between External and Commitment ( $\beta = 0.15$ ,  $p = 0.00$ ) is observed. The impact of moderators on different paths, as specified in Fig. 5-16, is summarized in Table 5-8.

Table 5-8 PLS estimated path coefficients for moderators

MODERATOR	PATH	COEFFICIENT	P-VALUE
CM	Communication -> Comfort	0.350	<0.01
SU	Competence -> Comfort	0.180	<0.01
SF	Comfort -> Creation	0.220	<0.01
QI	Creation -> Performance	0.750	<0.01

All moderators exerted a significant and positive impact on the corresponding path. Cellular Construction (CC) positively and significantly moderates the relationship between Communication and Comfort ( $\beta = 0.35$ ,  $p < 0.01$ ).

Furthermore, the moderator Setup Time Reduction (SU) significantly and positively impacted the relationship between Competence and Comfort ( $\beta = 0.18$ ,  $p < 0.01$ ). Similarly, Employee Involvement (EI) was a significantly positive moderator of the relationship between Comfort and Creation ( $\beta = 0.22$ ,  $p < 0.01$ ). Lastly, Quality Improvement (QI) was a significantly positive moderator of the relationship between Creation and Performance ( $\beta = 0.75$ ,  $p < 0.01$ ).

The results indicate that almost all of the impacts in the model are supported (Tables 5-1 to 5-6). The finding of Lean management, as a moderator, is perhaps one of the most interesting in this study. The use of Lean moderators changes the strength and direction of each VDC strategy and thus positively impacts companies' performance. In the VDC/Lean influence model, all Lean moderators exert a significant and positive impact on the path; SF and QI are those that allow better results between strategies. All paths between Lean variables coincide with the findings of Fullerton and Wempe (2009), with the exception of CM to Performance that is insignificant in our study.

Based on these results, we encourage companies to assess lessons learned and multiple communication channels before the implementation process begins, and extend their use throughout the implementation, with special emphasis during staff training. Also, we suggest that companies promote standardization with careful coaching and mentoring skills, rotations, strategic tasks, and competency assessments, and planning, so as to act proactively to unexpected events. Also, they should create mechanisms to capture,

communicate, and apply experience-generated learning and checklists. The results show that to improve workflow, it is necessary to incorporate VDC libraries, and meeting protocols (See Table 5-6 for more details).

The PLS method allowed us to assess the impact of each of the strategic components and external factors on performance. As we see in Table 5-9 the components People and Processes have the strongest impact on performance. The data were obtained from the total effect from the PLS method (Mandujano, 2016). The total effect is the sum of the direct effect and the indirect effect. The direct effect is a relationship linking two constructs with a single arrow, and the indirect effect is a relationship that involves a sequence of relationships with at least one intervening construct involved. As we said before, the technology is important to start the implementation, but in order to begin such implementation, it is crucial previously to have clear processes, availability and qualified staff (See Table 5-1). There is no point having technology if there are no structured processes and qualified personnel. It is crucial that companies align all their activities relating to people and process with their business strategy and vision, without losing focus on the technological aspects. The total direct and indirect effect of each factor on performance models could help to identify further research.

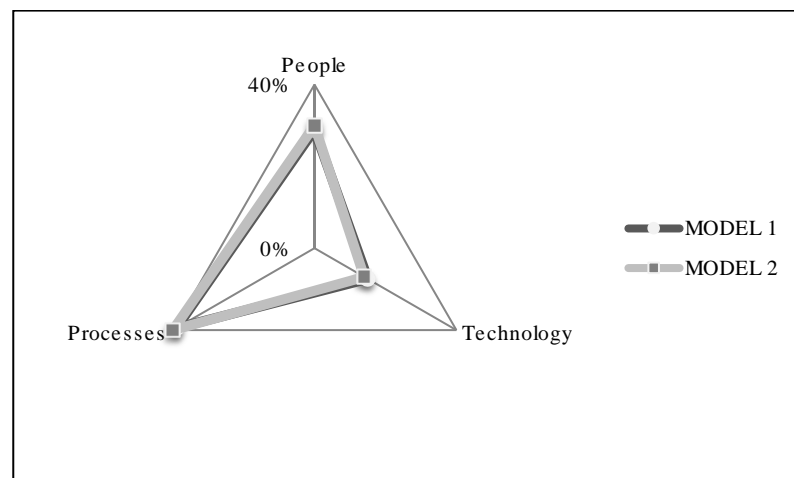


Figure 5-17 Impact of VDC in the different strategy components

Although the percentage of impact of the components models 1 and 2 are similar, the performance of model 2 has higher  $R^2=0.66$  over model 1 with  $R^2=0.10$ . From these two models, we can conclude that the more robust model was the one using the moderators. Model 2 suggests that the “Best Path Diagram” is: *External Factors -> Commitment -> Comfort -> Time Creation -> Performance* (Figure 5-18).

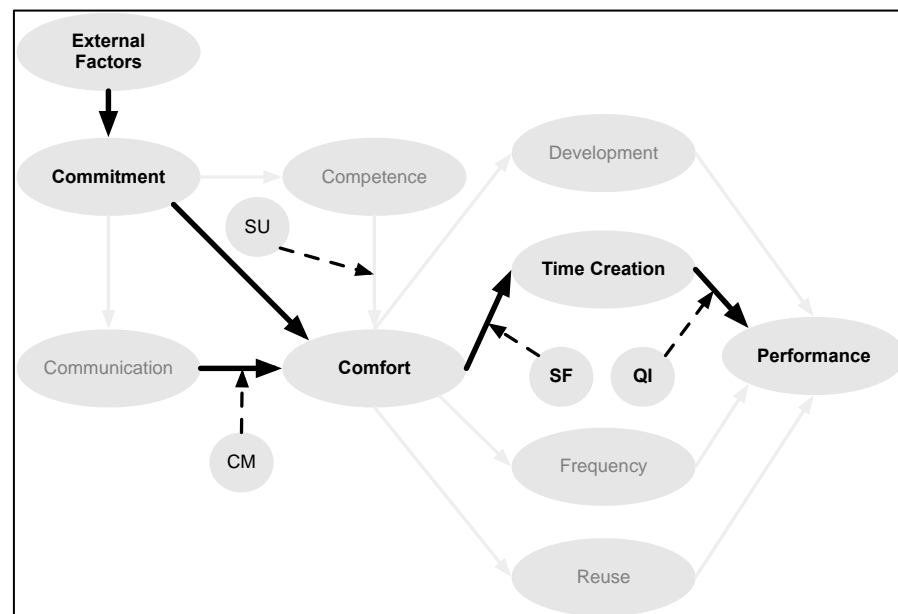


Figure 5-18 Best Path Diagram

The best path diagram is a result of evaluating not only one construct's direct effect on another but also its indirect effects via one or more constructs. That is the total effect (the sum of direct and indirect effects). The interpretation of the total effect is particularly useful in studies aimed at exploring the differential impact of several constructs on a criterion construct via one or more variables (Hair et al., 2013).

## 5.8 CONCLUSIONS

This study has academic and practical contributions. The main contribution for researchers is the modeling methodology to assess impacts of VDC implementation strategies on a company/project outcome, considering Lean as a moderator. The proposed model is based on the PLS method applied on a VDC/Lean influence model. Researchers can customize the VDC/Lean influence model conceptual model based on an existing set of data, as this paper presented as a test, or propose their own specific conceptual model for which then data has to be collected in order to run the PLS method. Another academic contribution is the conceptualization of the role that Lean management has on the impacts of VDC implementation strategies as moderators in the VDC/Lean influence model. Figure 5-16 suggests that the addition of Lean moderators increased the robustness of the conceptual model. The robustness of the models was validated through the coefficient of determination of model 2 ( $R^2=0.66$ ) over model 1 ( $R^2=0.10$ ).

Regarding the practical contributions, the testing of the methodology with CIFE's data provided insights about the relationship between VDC implementation variables and the company/project performance. The insights come not only from the PLS simulation results but also from the actual analysis and presentation of those results. These insights can support decisions on the implementation of VDC and Lean management in the industry. Companies can use these results to assess VDC strategies based not on anecdotes and beliefs about past projects but on a mathematical analysis.

Below, we present several conclusions based on the interpretation of the weights presented in tables 5-1 through 5-6.

1. Table 5-4 suggests that the use of models by competitors, the request from the owner, and the improvement of efficiency and process are the causes to start using VDC.
2. Table 5-4 suggests that management support is vital in the number of projects that use VDC for visualization, visualization and later as prediction, integration, or automation.

3. Tables 5-1 and 5-4 suggest there are several barriers for VDC implementation such as the contractual/regulatory environments and the lack of management support. These barriers translate into contract and financial provisions that impede sharing VDC data and models on projects (See Table 5-4). Based on this insight from table 5-4, we suggest it could also exist a fear of sharing models because of the responsibility associated with their use.
4. Table 5-1 suggests that companies should focus their efforts on establishing a contract with VDC elements before the implementation starts.
5. Table 5-2 suggests that companies should focus their efforts on create and update VDC from the earliest stages of the project, specifically in the design phase.
6. Software/hardware are significant in the use of VDC methods for your projects, but also the training of the company staff (See Table 5-3).
7. Table 5-6 suggests that to improve the quality in the VDC implementation, the results indicate to create checklists and mechanisms to capture, communicate and apply experience-generated learning.
8. Companies can design indicators to measuring an action before occurring residues and create communication channels and Kanban Boards (conflict resolution) (See Table 5-6).
9. Table 5-4 suggests that lack of technical expertise and the non- familiarity with the method were mentioned as reasons for not using VDC.
10. Finally, companies can focus on identifying and tracking conformance to weekly and final schedules as well as unbudgeted project changes to obtain improved performance results (See Table 5-5).

This study provides companies and researchers a better understanding of the factors leading to a successful VDC implementation and help managers to assess more effective implementation strategies. This research should affect how managers measure performance

and make decisions during projects, as well as to provide systematic tools to identify the best VDC implementation strategies.

## **5.9 LIMITATIONS AND FURTHER RESEARCH**

The research has limitations that need to be addressed in future research. First, we used an existing survey instead of capturing new data for the conceptual model. This decision limited the scope of the analysis of the VDC implementation and the use of Lean. Future research can define their own customized conceptual models including other constructs and moderators. There were problems with the variables' scales due to the non-uniformity of the responses. Also, we had to search for alternatives that best adapted to our model. In fact, the model was based on what people think (survey). To improve data it will be necessary to reduce bias in survey responses, through randomization, question wording, type and design and survey structure. It would be ideal to design a new collection tool with a comparable scale. The literature suggests a five or seven-point Likert-type scale (Vinzi et al., 2010). This would help, to a great extent, with the mathematical model. Second, companies and researchers should be careful about sample size (Hair et al., 2013). As is known, surveys tend to have a low response rate, so the design or/and selection of a new data collection tool, such as focus groups and case studies are presented as an option. Having case studies, in addition to the survey, will give a better connection with reality and will improve data validation. It would be ideal that the design of the new collection tool should be based on previously validated variables. Being previously validated ensures that the model will be within the allowed parameters. Moreover, we suggest that the new collection tool should incorporate variables related to Lean management to have more insights about their connection with VDC. Finally, we believe that this study is important to show how PLS can be used to analyze the impacts of VDC implementation strategies on the performance, with Lean management as a moderator.

In our opinion, the new insight into the VDC implementation strategies provides important and usable information to managers (For examples see sections 5.6 and 5.7). Nevertheless, this study needs to be replicated with new samples of companies and to be improved with the introduction of new and relevant variables, and perhaps the refinement of the scales used to measure the constructs. More areas of knowledge should benefit of the conceptual model such as computing, management, and any other area where researches or practitioners have to design strategies. Moreover, the conceptual model can become software in the near future.

## **5.10 ACKNOWLEDGMENTS**

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## **6 GENERAL CONCLUSIONS**

This chapter presents a discussion of theoretical and practical contributions. The chapter concludes with suggestions for future research.

### **6.1 OVERVIEW**

Incorporating new methods within the traditional and fragmented AEC industry requires practitioners to avoid getting stuck and moving to the forefront, delivering quality products, on time and within the budget. This thesis drew on three articles to reach the ultimate goal of this research.

First, I reviewed the literature to find new interactions that can help to complete the literature gap, thus create new implementation strategies. Furthermore, it was necessary to understand how the synergies between VDC and lean construction methods work. While it is possible to implement both methods independently to improve performance, this will improve further when these are considered concurrently. The literature review contributed to a better understanding of the impact of simultaneous implementations of lean construction principles and the VDC approach on various stages of construction projects. Identifying the interrelationship of lean philosophy with uses and actions performed through VDC enables a more holistic approach within the AEC. A significant number of interactions between lean construction and VDC were found. I suggested that when the entire VDC framework is used, the positive interactions between lean and VDC increase significantly in comparison to the same analysis restricted to the interaction between lean construction and BIM. To support this I tested previously hypotheses mentioned in the literature to clarify the VDC and lean panorama and the connection between both methods.

These interactions can help to complement findings from previous studies and create new implementation strategies in the future.

Second, I identified examples of waste in VDC practice from a lean thinking perspective. The research method applied was a broad survey and an analysis that described the actual implementation of VDC and lean construction. This analysis refers to methods that focus on contrasting and combining results from different studies, in the hope of identifying patterns among study results, sources of disagreement among those results, or other interesting relationships that may come to light in the context of multiple studies. I proposed lean methods to reduce waste within the VDC information flow. For example, using a set-based design can help reduce non-value-added processing. Value-Stream Mapping (VSM), a diagram of every step involved in the material and information flows needed to bring a product from order to delivery, can help reduce overproduction. Moreover, gathering people and/or processes to improve workflow, for example, protocols for sharing models, BIM libraries, meeting protocols, and quality protocols can help reduce inventory (excess).

Third, I designed a VDC/Lean influence model that will allow architecture, engineering, and construction (AEC) companies to design virtual and design construction (VDC) implementation strategies, including lean management concepts. VDC/Lean influence model is based on a conceptual model and a mathematical model. The conceptual model is a simplified model of implementation variables and interactions that influence project performance. Given the strong synergies between VDC and lean construction, I proposed lean as a moderator for the conceptual model. The mathematical model uses Partial Least Squares (PLS), which helps to explain the relationships among the multiple variables. Data from CIFE survey, helped to test the modeling methodology and its analysis capabilities.

Despite the exploratory nature of the study, the research provided interesting insights into the field. Companies can use the proposed model to design a VDC strategy based on a

mathematical analysis rather than anecdotes. After this last paper I answered the research questions (See section 2.1.4). This study proposed two hypotheses:

1. *Current implementation of VDC in projects and companies are suboptimal, with even the most apparently successful cases often missing many opportunities.*
  - In chapter 5, we had three types of companies: high, medium, and high performance. High performance companies are the most apparently successful cases. But as we note in section 5.6, specifically figures 5-6, 5-9, 5-11, and 5-13, their current degree of VDC implementation (time creation, development, reuse...) is not full at all. Only half of high performance companies emphasized the VDC implementation in all the phases. Moreover, as we see in figure 5-8, the consequences of using VDC are relative low from the total of companies (100%). As I mentioned in the paper, companies need to feel the benefits that VDC provide, e.g. beginning in pilot projects.
2. *A systematic study of project and company implementation strategies can provide a better understanding of the factors leading to a successful implementation and help managers design more effective implementation strategies.*
  - The main contribution of this study to the body-of-knowledge is the development of a VDC/Lean influence model that bridged the adoption gap by helping companies and researchers to model the impacts of VDC implementation strategies on companies' performance, incorporating lean management as a moderator. Data from a VDC survey tested the VDC/Lean influence model and its analysis capabilities through the use of PLS. The influence model has a direct contribution for research and industrial sector. Companies can use the proposed model to design VDC strategies, based not on anecdotes and beliefs about past projects but on a mathematical analysis. This study provides companies and researchers a better understanding of the factors leading to a successful VDC implementation and help managers to design more

effective implementation strategies. Achieving the objectives of this research should affect how managers measure performance and make decisions during projects, as well as provide systematic tools to identify the best VDC implementation strategies.

## **6.2 CONTRIBUTIONS**

This section discusses the theoretical and practical contributions of the research.

### **6.2.1 THEORETICAL CONTRIBUTION**

The theoretical contributions of this research are:

The main contribution to the body-of-knowledge of the VDC and Lean literature is a VDC/Lean influence model (C-C-C model) (See Figure 5-5) that bridges the adoption gap with its model of causal relationships among different factors related to the implementation of VDC by AEC companies and the impact of Lean moderators on the outcome. Researchers now can use this model to help identify the best VDC implementation strategies, including lean management concepts as a moderator.

In the VDC/Lean influence model each question of the survey is related to a variable: Strategic Components (People, Processes, and Technology), External Factor, Performance, and Lean management as a moderator. The Strategic Components are composed by a set of Alternatives. The VDC/Lean influence model (C-C-C model) is a contribution to the theoretical literature of VDC and Lean based on the evidence summarized in Figure 5-16 and the associated tables 5-1 to 5-6.

## 6.2.2 IMPLICATIONS FOR PRACTICE

The methodology filled a gap in the VDC implementation process by helping AEC companies identify strategies for successful VDC implementations and connections to lean philosophy. Achieving the objectives of this research should affect how managers measure performance and make decisions during projects, as well as provide systematic tools to identify the best VDC implementation strategies. The VDC/Lean influence model will help companies to have a better understanding of the factors leading to a successful VDC implementation and help managers design more effective strategies.

## 6.3 FUTURE RESEARCH DIRECTIONS

There are several aspects of this research that I was unable to anticipate or that could have been executed differently. It is advisable for future researchers to take this into account if they pursue similar researches. I will follow discuss future research directions:

- Building on a particular finding in my research.
  - *Findings that I did not anticipate:* Within my dissertation I had some findings that I did not anticipate from the start. These are useful for making future research suggestions because they can lead to entirely new avenues to explore in future studies.
    - Chapter 4 reported and discussed a part of VDC practices that has not been systematically studied: waste within the implementation of VDC. Moreover, the literature survey found many references to waste in the VDC literature, which suggested that the waste exists in current practice. I suggested that current practice is a root cause of the waste problem, and Lean methods, such lean office and lean it, can help to address the problem.

This paper was a stepping stone in my doctoral research, in fact after this study I could incorporated Lean to the my model. From this future researches can focus in see lean as an initiative that can "branch" throughout all processes of VDC, including information flow. Also, researches can validate or add lean recommendations to reduce waste within VDC practice. Maybe with some case studies, interviews, focus groups or surveys.

- PLS is a powerful method that has been underestimated in the AEC industry, possibly because it is a sector in which quantitatively strategies are not measured. The total direct and indirect effect of each factor on performance models could help to identify further researches. Researches can use the results in paper 3, to design more strategies focuses on people, processes, and finally technology.
- *Re-evaluating the VDC/Lean influence model:* It is necessary to replicate the VDC/Lean influence model with new samples of companies, may be through case studies, to validate the model but also to have a more connection with the reality.
- *Expanding a conceptual model:* Researches can examine new constructs (or indicators) that were, or not, included in the VDC/Lean influence model. Also, they can add new constructs (or indicators) to have new insights for the *construction sector*.
- The results of this research could be used to improve CIFE survey or even create new focus solely on VDC implementation strategies.
- Researches could incorporate and view lean as a moderator in the CIFE survey, or a new collection tool, to allow a more efficient VDC implementation.

- Researches can use the proposed VDC/Lean influence model, to begin a new study with all the variables validated.
- Building for the AEC industry.
  - Facility Management (FM) is a future, unexplored niche for VDC and Lean. Future researches could focus on this VDC feature and create new interactions with lean.
  - In the future, a new data collection can offer evidence of short range and long-range growth opportunities for new methodologies, with lean as a framework.
  - More areas of knowledge should benefit of the conceptual model such as computing, management, and any other area where researches or practitioners have to design strategies.
  - Moreover, the conceptual model can become software for design strategies in the near future. Not only for the AEC industry, but for any interested sector.

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