Estudio de la implementacion y beneficios del diseño y construcción virtual utilizando un enfoque bayesiano

A study of virtual design and construction implementation and benefits using a bayesian approach

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Resumen

Tanto los profesionales como los investigadores en el campo de la gestión de la construcción carecen de métodos confiables y prácticos para evaluar las proposiciones de valor de métodos emergentes tales como el Diseño y Construcción Virtual (VDC) incluyendo el entendimiento de cómo diferentes niveles de implementación afectan los beneficios esperados. Más aun, los métodos actuales para entender la implementación y los beneficios de VDC no pueden ser actualizados fácilmente para incorporar nuevos datos. Este artículo presenta un marco de referencia bayesiano para la predicción de los beneficios de la aplicación de VDC a partir de datos respecto a su implementación. Analizamos datos de 40 proyectos que realizaron la modelación formal de parte del alcance del proyecto y/o el proceso de construcción. El análisis sugiere que niveles más altos o más amplios de implementación de VDC llevan a beneficios más altos para el proyecto. Explicamos el uso de un marco de referencia bayesiano como alternativa a la aplicación de la teoría clásica de la probabilidad en la investigación sobre gestión de la construcción, como usamos el marco bayesiano para interpretar datos acerca de la práctica y resultados de la implementación de VDC, nuestros resultados que indican que los beneficios de la aplicación de VDC tienen una fuerte correlación contingente positiva con el nivel de implementación de VDC en los proyectos, y nuestra propuesta de utilización del método propuesto para actualizar las conclusiones acerca de los beneficios de implementar VDC cuando cambian los datos acerca de su implementación y resultados.

Palabras clave: Bayes, Bayesiano, VDC, Gestión de la Construcción, 3D, 4D.

Abstract

Practitioners and construction management researchers lack believable and practical methods to assess the value proposition of emerging methods such as Virtual Design and Construction (VDC) including understanding how different levels of implementation affect its benefits. Furthermore, current methods of understanding VDC implementation and benefits cannot be updated easily to incorporate new data. This paper presents a Bayesian framework to predict benefits from application of Virtual Design and Construction (VDC) given data about its implementation. We analyzed data from 40 projects that performed some formal modeling of the project scope and/or the construction process. The analysis suggests that more extensive or higher levels of VDC implementation lead to higher project benefits. We explain the use of a Bayesian framework as an alternative to the application of classical probability theory to construction management research, how we used it to interpret data about VDC practice and outcomes, our finding that benefits have strong positive contingent correlation with the level of VDC implemented on projects, and our suggestion to use the method to update conclusions about benefits given changing data about implementation and outcomes.

***Key words**: Bayes, Bayesian, VDC, Construction Management, 3D, 4D.*

1. Introduction

The field of statistics has long embraced the concept of probability models for data. It is rare to find leading scientists writing in the last three hundred years who did not employ notions of probability when advocating their own ideas or reviewing those of others (Howson, 1993, Dorling, 1979). Probability models of data typically involve parameters that are presumed to be related to characteristics of the sampled populations. These parameters can range from few in number with simple interpretations to an uncountable number. Parameter values can never be known with absolute certainty unless entire populations are sampled (Christensen et al., 2011).

The huge variation and quantity of unique construction industry projects and organizations across time and space make it very difficult, if not impossible, to sample entire populations for construction management (CM) research purposes. Construction projects are unique (i.e., situations cannot be duplicated), and although some information may be available regarding past occurrences in similar situations, no information in the form of observed frequencies is available regarding repeated trials under identical conditions (Winkler, 1972). Thus, CM research has many events that can be thought about in a probabilistic sense, but the unique data do not allow a strict relative-frequency interpretation (Winkler, 1972). We use a Bayesian approach to CM research in this paper as a model to assess the current understanding of Virtual Design and Construction (VDC) implementation and benefits. This approach updates conclusions about dependence of benefits on level of VDC implementation with new information as such information becomes available with new projects. We applied the Bayesian approach to analyze data from 40 case projects to study how the level of benefits depends on the level of VDC implementation.

2. Virtual Design and Construction (VDC)

The Center for Integrated Facility Engineering (CIFE) at Stanford University defines Virtual Design and Construction (VDC) formally as the use of multi-disciplinary performance models of design-construction projects, including the product (i.e., facilities), work processes, and organization of the design-construction team to support business objectives. For this study, a VDC model is a computational model that represents any or several of the product, organization, and process of a project. VDC models individually or collectively can be used as input to model-based analyses to predict many behaviors such as product quantities, project costs for an organization, schedule performance, and clashes in 3D and 4D.

A project team can and must control three aspects of a project: the design of the product to be built, the design of the organization that does the design and construction, and the design of the design-construction process that the organization follows. The aggregation of VDC models into a Product-Organization-Process model is called a POP model. CIFE researchers created a POP modeling methodology to allow team members to request and use the VDC models they need to participate effectively in the design, understand all VDC models as they evolve, and express their perspectives in a timely manner to other team members throughout the project (Kunz and Fischer, 2011).

VDC and BIM (a VDC method) are now widely and dramatically changing the process by which buildings are designed and constructed (Giel and Issa, 2011; LeFevre 2011). These changes are now occurring at an accelerated pace (Sacks et al, 2010; McGraw Hill, 2009; Gilligan and Kunz, 2007). So far, construction industry professionals and researchers have constructed their knowledge about the implementation and benefits of VDC through their own experiences and through sharing experiences, mostly in an ad-hoc and anecdotal way (Gao, 2011). This knowledge of construction practice is limited and developing slowly in the context of the acceleration of changes we observe in industry. Numerically substantiating VDC benefits given a level of VDC implementation demonstrated by research is a task that has been unattainable at a large scale and at the rate at which it could match the rate of change in industry seen today.

3. The POP Modeling Methodology

The POP model aggregates the content of the Product (e.g., 3D CAD, BIM), Organization, and Process models, each of which is produced using its own modeling tool (e.g., Revit, SimVision, Navisworks, Primavera, etc.). A POP model defines conceptual elements that are shared and help the project team members to assure that the product, organization, and process specifications are appropriate and mutually consistent. VDC makes the semantics of data explicit so that practitioners can share them between different perspectives and applications (Kunz and Fischer, 2011). For example, the product model defines the physical elements to be designed and built, at some selected but necessarily incomplete level of detail (AIA, 2008). The organization model defines the groups that design and build each defined physical element, and the process model defines the activities and milestones that team members follow to do their work.

At a high level, POP models represent the *functions* (Column 2 in Table 1), *form or scope* as designed by the project team in response to functions (Column 3), and predicted or measured *behaviors* of the product, organization and process for a project (Column 4). Project elements include descriptions of the product, typically a facility (Row 2), the organization that designs and builds the facility (Row 3), and the process that the organization follows as it does its project work (Row 4). Note that Building Information Models (BIM) represent the form/scope of the product, which is a crucial but by far not the only portion of the total perspective of a project.

POP models are defined using the classic function –form– behavior taxonomy of design theory (Gero 1990, Clayton et al 1996):

- Function, or design intent, represents the intent of the owner or the requirement of a critical stakeholder such as the code jurisdiction, e.g., an auditorium should seat 100; an organization should include a licensed structural engineer; and the design process should include certain review milestones.
- Form, or scope, which the project team specifies, designs, and builds in response to the functions. Examples include choice of specific spaces, the choice of a particular contractual relationship between the architect and general contractor, and the construction plan.
- Behavior, or performance, includes predicted behaviors of the design and measured behaviors of the product, organization, or process. Examples include the predicted deflection of a beam, measured hours spent by a contractor doing a task, and predicted duration of the construction phase.

4. VDC Implementation and Benefits

Professionals and researchers are asking for simple models to relate investments in innovations such as VDC models to benefits. However, the current understanding of VDC implementation and benefits has been developed mainly through anecdotal approaches (Gao, 2011; Kunz and Fischer, 2011). Current methods of understanding VDC implementation and benefits cannot be updated formally or easily to incorporate new data and information and update the understanding. Anecdotally, VDC on individual projects incur real costs as developers recreate or reenter information in their models, often developing design details, take-offs, etc. several times though different stages in the design and construction process (Laitinen, 1998). However, users report that they use VDC methods and receive value from its use in spite of the limitations that they acknowledge (Kunz and Fischer, 2011). This paper assesses the current understanding of VDC implementation and benefits using a Bayesian model that defines and correlates statistically the events "level of VDC implementation" with "observed benefits."

5. Research in Construction Management

Construction projects are extremely dynamic and complex and consist of multiple interdependent components (Love et al, 2002). These have multiple interacting feedback processes and non-linear relationships. In addition, they are essentially human enterprises, and cannot be understood solely in terms of technical relationships among components and from a purely scientific approach (Love et al, 2002). Complexity, defined as the extent of collaboration of multiple disciplines and individuals to perform a task, is an inherent characteristic of construction leading to a wide range and diversity of phenomena that CM

Table 1. *Content of POP Models (Kunz and Fischer, 2011)*

	Function: Objectives	Form/Scope: Design choices	Behavior: Predictions
Product	Spaces, elements, and systems	Designed spaces, elements, and systems	Cost ($), time (t), energy consumption (e.g. Kw/h/sq2)
	Measurable Objectives	Values	Predictions; measured values
Organization	Actors	Selected actors	Cost (hours or $)
	Measurable Objectives	Values	Predictions; assessed values
Process	Tasks	Designed tasks	Cost ($), duration (t)
	Measurable Objectives	Values	Predictions; assessed values

researchers try to probe (Seymour et al., 1997; Chau et al., 1998; Harris, 1998; Li and Love, 1998).

CM academicians propose different (generic) research methods for their research problems (Love et al, 2002; Seymour and Rooke, 1995; Raftery et al., 1997; Runeson, 1997; Seymour et al., 1997; Chau et al., 1998; Li and Love, 1998; Holt and Faniran, 2000). This study of VDC implementation and benefits sets up a Bayesian approach as a research method to assess the current and future understanding of VDC implementation and benefits as part of CM research.

The next sections discuss the relationship between basic statistical concepts and construction management research, summarizes the current use of probabilistic approaches for carrying out construction management research, and introduces our use of the Bayesian approach.

6. Construction Management Research Using Probabilities

The nature of construction management research makes it difficult to identify with precision the relationship between parameters of independent controllable events (e.g., budgets, plans and schedules) and measured values that represent dependent outcomes. It is also difficult to observe enough experiments to create probabilities that believably predict long-term average outcomes. Even though the long run frequency of certain types of data that occur over repeated trials is an intrinsic characteristic of the construction industry, these data are so disparate in space and time that their storage in large databases have not even been attempted. Furthermore, when applying concepts of probability to research the benefits of innovative tools, methods or knowledge, the rarer the event, the higher the error in the estimation of its probability, with a small measurement error of the variability leading to a significant under-estimation of the probability (Taleb, 2010).

The populist view of probability is the so-called frequentist approach, whereby the probability P of an uncertain event A, P(A), is defined by the frequency of that event based on previous observations (Christensen et al, 2011; Winkler, 1972; Howson and Urbach, 1993; Glickman and van Dyk, 2009). The frequentist approach for defining the probability of an uncertain event (i.e., the outcome values of a construction project) would be precise if it was possible to record enough accurate information about many past instances of the event or to design and run random experiments to produce enough outcome values for probabilistic models. In construction, these events are unique, i.e., the situations cannot be duplicated. Although some information may be available regarding past occurrences in similar situations, not enough information is available in the form of observed frequencies from repeated trials under identical conditions. Since a historical or fabricated database with enough event values does not exist for the successful application of the frequentist approach to construction management research, a fundamentally different experimental approach is needed.

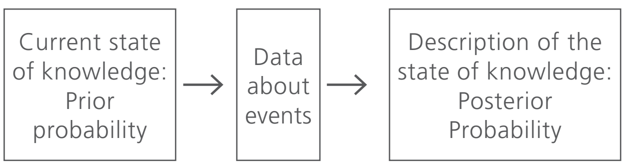
In construction, it is not possible to observe repetitive trials of the same uncertain situation. Thus, the frequency-based probability approach (e.g. outcomes, frequencies) cannot explain outcomes (Winkler, 1972). Therefore, we used Bayes' theorem (Howson and Urbach, 1993) to update beliefs given initial and emerging evidence about VDC implementation and benefits. Specifically, we applied the Bayesian approach to verify beliefs about VDC implementation and benefits given some scarce evidence of project improvements (i.e., benefits) due to VDC implementation. Based on data about VDC implementation and benefits on 40 case projects, we tested the prior beliefs about VDC implementation as the cause of project benefits to represent knowledge about the relationship between VDC implementation and benefits given the case data.

7. Bayesian Approach to Construction Management Research

Bayesian induction treats the probabilities as a property of our attitude towards them; such probabilities represent degrees of belief (Christensen et al, 2011; Winkler, 1972; Howson and Urbach, 1993; Glickman and van Dyk, 2009). A frequentist approach uses probability to express the frequency of certain types of data to occur over repeated trials, a Bayesian approach uses probability to express belief in a statement about unknown quantities (Glickman and van Dyk, 2009). The scientific methodology based on this concept is usually referred to as the methodology of Bayesianism because of the prominent role it assigns to a famous result of the probability calculus known as Bayes' Theorem (Howson and Urbach, 1993).

Bayesian statistics is primarily a tool to evaluate relative evidence (Christensen et al, 2011), which is the case for most construction management research. Bayes' Theorem regulates the way in which beliefs are updated on the receipt of evidence (Howson and Urbach, 1993). Bayesian statistics starts by using (prior) probabilities to describe the current state of knowledge. It then incorporates information through the collection of data and creates new (posterior) probabilities to describe the state of knowledge after combining the prior probabilities with the new data (Figure 1). In Bayesian statistics, all uncertainty and all information are incorporated through the use of probability distributions, and all conclusions obey the laws of probability theory (Christensen et al, 2011). Since it focuses on clarity of meaning rather than «rigor» in the narrow mathematical sense, Bayesian thinking can provide an alternative research approach to understand specific situations. For these same reasons, other researchers have also applied Bayesian statistics to construction management problems, e.g., to evaluate schedule risks (Nasir et al., 2003), assess construction performance (McCabe et al., 1998), or update cost and schedule information for marine structures (Blair et al., 2001).

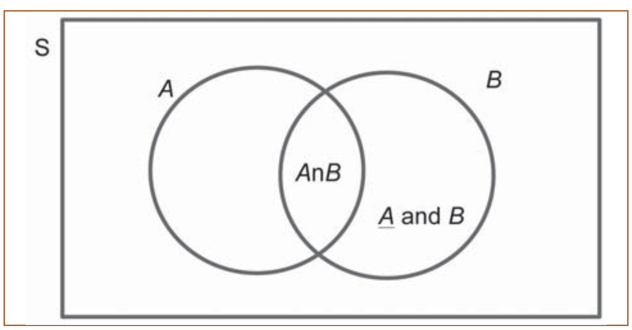
Figure 1. *Schematic representation of the Bayesian approach*



8. The Bayes Theorem

Bayes' Theorem provides a convenient formula that establishes relationships among various conditional probabilities (Figure 2).

Figure 2. *Relationships among various conditional probabilities*



The simplest version of this theorem can be stated as follows (Winkler, 1972):

Equation 1. *Bayes Theorem*

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B|A)P(A) + P(B|\underline{A})P(\underline{A})}$$

Where:

- $\underline{A}$ represents the complement of the event A (that is, "not A")
- P(X) is the probability of occurrence of event X
- $P(X|Y)$ is the conditional probability of event X given that event Y occurred

Equation 1 is a convenient formula that establishes the relationship among various conditional probabilities (Winkler, 1972). P(A) represents the *prior* information. A sample is then observed, and the outcome of the sample can be summarized by B which is the observed value of a random variable. The probabilities P(B/A) are called *likelihoods* and are determined from the conditional values of B given different values of A. Using Bayes' theorem, the *prior* information and the sample information (represented by the *likelihoods*) are combined to obtain the *posterior* information of A: P(A/B). The *posterior* information then summarizes the information concerning A, given the sample outcome B (Winkler, 1972).

The adjectives "prior" and "posterior" are relative terms relating to the observed sample. If after observing a particular sample and computing the posterior information of A, it is decided that another sample will be taken, the information just computed would now be the *prior* relative to the new sample (Winkler, 1972).

Bayes' Theorem, also called the Bayes rule or formula (Cargal, 1988), can be put into a more general form. If the *J* $A1$, A_2, ..., A_j events are mutually exclusive, i.e., no two of the events can both occur; if one of them occurs, none of the other *J* -1 can occur, and collectively exhaustive, i.e., one of the events must occur; the *J* events exhaust all of the possible results, and *B* is another event (the "given" event), then:

Equation 2. *General form of Bayes' Theorem*

$$P(A_j|B) = \frac{P(B|A_j)\,P(A_j)}{P(B|A_1)P(A_1) + P(B|A_2)P(A_2) + \dots + P(B|A_j)P(A_j)}$$

for any event A_j, where *j* is an integer between 1 and *J*, inclusive.

9. Considerations for the Application of Bayes' Theorem to Study VDC Implementation and Benefits

We used the Bayes inductive probability approach to find the dependency between *'Project Benefits'* and *'VDC implementation'* events.

9.1. Level of project improvement (data):

We defined a project benefit as an event that aggregates into a single category, perceived or documented, project outcomes in terms of schedule, cost, and quality improvement after the construction project is finished.

We categorized benefits into three levels:
a) Dramatic Improvements
b) Medium Improvements
c) Small Improvements

Each level considers a combination (i.e., an outcome) and a variation in the intensity of the traditional construction project outcome values (e.g., cost and/or schedule reduction, coordination improvements, increased productivity, etc.) (Fischer et al., 2003).

9.2. Level of VDC implementation

We considered VDC implementation as the independent parameter for the application of the Bayes' theorem. Bayes theorem represents the contingent probability of occurrence of dependent events on independently occurring events. While some projects employ only product modeling, i.e., BIM, other projects model the product and the processes and others the product, organization, and processes. We defined the level of VDC implementation in terms of the scope of the VDC modeling using the three types of models defined by the POP methodology:

a) VDC1: only Product Modeling was applied
b) VDC2: Product and Process Modeling was applied
c) VDC3: Product, Process, and Organizational modeling was applied

9.3. Bayes' Formula applied to the VDC study

Based on equation 2, applying the Bayes' theorem to study the relationship between VDC implementation and benefits leads to Equation 3:

Equation 3

$$P(VDCi|B) = \frac{P(VDCi)\,P(B|VDCi)}{\Sigma P(VDCi)\,P(B|VDCi)}$$

for i= 1,2,3

Where:
- B = Event: An observed Dramatic, Medium or Small Improvement
- VDCi = Event: VDC application at level 1, 2, or 3
- P(VDCi,B) = P(VDCi)P(B|VDCi) since VDCi and B are dependent events because knowledge about one changes the probability of occurrence of the other.
- P(VDCi|B) = Probability that VDCi was the cause of a Dramatic, Medium, or Small Improvement given that the improvement already occurred.
- P(VDCi): Probability of occurrence of VDC implementation at a level i, where i=1, 2, 3. In Bayesian terms this is also called the prior and it is the knowledge about the parameters before data are observed.
- P(B|VDCi) = Probability of occurrence of an improvement given that VDC was applied at some level of VDC implementation.
- P(B) = ΣP(VDCi) P(B|VDCi): Total probability of an improvement occurrence.

To facilitate the application of Bayes' formula to study the benefits of VDC implementations, we used a tabular approach (Table 2). Once the table is completed with data and calculations, the total probability of an improvement occurrence (Σ Column 4) can be related to each row in Column 5 (Bayes formula results) to make inferences about VDC implementation as the cause of project improvements without the need to consider the rest of the data and calculations.

10. Application of Bayes' Theorem to Study VDC Benefits

We applied the Bayes' theorem using the tabular approach in Table 2 to analyze the relation between VDC implementation and project benefits using data from 40 case projects.

10.1. Data and Bayes formula application

As part of a research project to develop a framework to capture, describe and organize the characteristics of 3D/4D modeling implementations, 3D/4D modeling practices were studied by Gao (2011) on forty case

Table 2. *Tabular format to represent independent (Column1, 2) and dependent (Column 3) events and probabilities*

Column 1	Column 2	Column 3	Column 4	Column 5 Bayes Formula
Independent events	P(VDCi)	P(B|VDCi)	P(VDCi) P(B|VDCi)	P(VDCi)P(B|VDCi) ΣP(VDCi) P(B/VDCi)
VDC1	Number of projects at VDC level 1 / Total number of projects	D, M or S Improvement / Number of projects at VDC level 1	Column 2 x Column 3	Column 4 / Σ Column 4
VDC2	Number of projects at VDC level 2 / Total number of projects	D, M or S Improvement / Number of projects at VDC level 2	Column 2 x Column 3	Column 4 / Σ Column 4
VDC3	Number of projects at VDC level 3 / Total number of projects	D, M or S Improvement / Number of projects at VDC level 3	Column 2 x Column 3	Column 4 / Σ Column 4
			ΣP(VDCi)P(B/VDCi)	

D=Dramatic; M=Medium; S=Small

projects. Product modeling (3D) was implemented in 13 projects (33%), while Product (3D) and Process Modeling (4D) were implemented in 27 projects (68%). Then the values for P(VDCi) are:

- P(VDC1) = 33%
- P(VDC2) = 68%
- P(VDC3) = 0%

All the projects were commercial. CIFE researchers, students, and visitors observed or helped many of the case projects with the implementation of BIM and 4D modeling. On the other projects, 3D/4D modeling was carried out by AEC organizations in Finland. The projects range from a few million dollars to several hundred million dollars in size, include public and private projects in a range of construction sectors (residential, commercial, institutional, industrial, and transportation), and were delivered with several contractual arrangements (design-bid-build, design/build, and CM/GC). Empirical data for the case studies came from two sources of evidence: available documents and interviews using a list of questions as the data collection tool (Gao, 2011).

Based on the gathered data, the research team assigned each project the level of project improvement defined in section 9.1. Table 3 and Table 4 show the detail as well as the summary of the level of project improvement and the level of VDC implementation for each project.

10.2. Results

Table 5, Table 6 and Table 7 show the results of the application of Bayes Formula for each level of project benefit (i.e., Dramatic, Medium, and Small). These results constitute a specific scenario related to the data shown in Tables 2 and 3. Data of VDC application at level 3 (i.e., organization modeling) were not found on the 40 case projects and are therefore not included in this research. However, we included VDC3 in the results with zero values, because organization modeling is part of the theoretical foundation of VDC. Future research utilizing our Bayesian model should look for VDC application at level 3 and a higher quantity of case projects.

Column 1: P(VDCi) is the same for the three tables and represents the prior knowledge about the distribution of VDC implementation among the three defined VDC levels of implementation in the 40 case projects before data were observed. In 13 projects VDC was implemented at level 1 (VDC1=33%), in 27 projects VDC was implemented at level 2 (VDC2=68%), and in 0 projects VDC was implemented at level 3 (VDC3=0%).

Column 2: P(B|VDCi) relates the event B (number of projects where observed dramatic, medium or small improvements were reported) with the event VDC implementation (number of projects where VDC was implemented at level 1, 2 or 3). In the second row of Table 5, for example, 26% represents that in 7 of the

Table 3. *Assessed level of project improvement for projects that applied BIM only, i.e., had an independent variable value of VDC Level 1 implementation.*

(A)

Project N°	VDC Level	Project Improvement
1	1	Small
2	1	Medium
3	1	Medium
4	1	Medium
5	1	Medium
6	1	Medium
7	1	Medium
8	1	Medium
9	1	Medium
10	1	Small
11	1	Small
12	1	Small
13	1	Small

(B)

Summary (VDC1):

Project Improvement	N° of projects	
Dramatic	0	0%
Medium	8	62%
Small	5	38%
Total:	**13**	

Table 4. *Assessed level of project improvement for projects that applied BIM and process modeling, i.e., had an independent variable value of VDC Level 2 implementation.*

(A)

Project N°	VDC Level	Project Improvement
1	2	Small
2	2	Dramatic
3	2	Medium
4	2	Medium
5	2	Dramatic
6	2	Medium
7	2	Medium
8	2	Dramatic
9	2	Medium
10	2	Medium
11	2	Medium
12	2	Medium
13	2	Dramatic
14	2	Small
15	2	Small
16	2	Small
17	2	Small
18	2	Dramatic
19	2	Medium
20	2	Medium
21	2	Dramatic
22	2	Medium
23	2	Dramatic
24	2	Small
25	2	Small
26	2	Small
27	2	Medium

(B)

Summary (VDC1):

Project Improvement	N° of projects	
Dramatic	7	26%
Medium	12	44%
Small	8	30%
Total:	**27**	

Table 5. *Bayesian analysis for events with outcome of dramatic Improvements*

		1 column	2 column	3 column	4 column
			Dramatic Improvements		
		P(VDCi)	P(B|VDCi)	P(VDCi)^P(B|VDCi)	Bayes Formula P(VDCi|B)
row 1	VDC1	33%	0%	0%	0.0%
row 2	VDC2	68%	26%	18%	100.0%
row 3	VDC3	0%	0%	0%	0.0%
	Total Probability of an Improvement occurrence:			18%	

Table 6.≠ *Bayesian analysis for events with outcomes of medium improvements*

		1 column	2 column	3 column	4 column
			Medium Improvements		
		P(VDCi)	P(B|VDCi)	P(VDCi)^P(B|VDCi)	Bayes Formula P(VDCi|B)
row 1	VDC1	33%	62%	20%	40.0%
row 2	VDC2	68%	44%	30%	60.0%
row 3	VDC3	0%	0%	0%	0.0%
	Total Probability of an Improvement occurrence:			50%	

Table 7. *Bayesian analysis for events with outcomes of small improvements*

		1 column	2 column	3 column	4 column
			Small Improvements		
		P(VDCi)	P(B|VDCi)	P(VDCi)^P(B|VDCi)	Bayes Formula P(VDCi|B)
row 1	VDC1	33%	38%	13%	38.5%
row 2	VDC2	68%	30%	20%	61.5%
row 3	VDC3	0%	0%	0%	0.0%
	Total Probability of an Improvement occurrence:			50%	

27 projects where VDC was implemented at level 2 (which represents 68% of the 40 projects), a dramatic improvement was reported.

Column 3: P(VDCi)^P(B|VDCi) is the joint probability of occurrence of the events VDC and B, P(VDCi,B). For example, in the second row of Table 6 for medium benefit, 30% represents that in 12 (which represents 44% of the 27 projects where VDC was implemented at level 2) of the 27 projects (which represents 68% of the total number of projects and where VDC was implemented at level 2), medium improvements were reported. This example shows that, within this context, the probability of obtaining a medium improvement if VDC is implemented at level 2 is 30%. In the first row of this table, 20% represents the probability of obtaining a medium improvement if VDC is implemented at level 1. The addition of all the probabilities in column 3 gives the total probability of obtaining a dramatic, medium or small Improvements considering the prior knowledge about the distribution of VDC implementation depicted in column 1 for each of the three tables. Hence, considering the data of the research presented in this study, the probability of obtaining dramatic Improvements is 18%, the probability of obtaining medium improvements is 50%, and the probability of obtaining small improvements is 33%.

Column 4: P(VDCi|B) shows the result of the application of the Bayes formula and represents the posterior distribution, the knowledge after seeing the data about improvements in the case projects.

10.3 Interpretation

In Table 5, Table 6 and Table 7, for dramatic, medium, and small improvements, the percentage of improvements in column 3 is always higher when VDC was implemented at level 2 rather than when VDC was implemented at level 1. We interpret the results of these tables as evidence that the probability of occurrence of improvements is higher with a higher level of VDC implementation.

Table 8 summarizes the relationships between VDC implementation and benefits for the scenario where the probability of VDC implementation at level 1 is 33% and the probability of VDC implementation at level 2 is 68%.

We interpret the results of Table 8 as evidence that:

- The probability of medium improvements as a result of VDC implementation is the highest (i.e., 50% probability of medium improvements);
- Dramatic improvements are achieved only when VDC is implemented above level 1 (i.e., 0% in the intersection between the row "Dramatic" and the column "VDC1")
- When higher the level of VDC implementation, higher the probability of VDC as the cause of the improvements (i.e., values in column VDC2 always higher than values in column VDC1)

10.4. Inferences based in the existing and new hypothetical scenarios

Table 9 shows the results for a new hypothetical scenario where the probability of VDC implementation at level 1 is 10%, the probability of VDC implementation at level 2 is 90%, and the distribution between dramatic, medium, and small improvements is maintained as shown in tables 3.B and 4.B,

Table 8: *Summary of the relationships between VDC implementation and benefits*

		VDC1	VDC2	VDC3
Probability of VDC Implementation:		33%	68%	0%
Type of Improvement	Probaility of Occurrence of the Improvement	Probability of VDC as the cause of the Improvement		
		VDC1	VDC2	VDC3
Dramatic	18%	0%	100%	0%
Medium	50%	40%	60%	0%
Small	33%	38%	62%	0%

Table 9: *Hypothetical scenario in which the use of VDC Level 2 increases and the likelihood of* ***benefits remains*** *constant*

		VDC1	VDC2	VDC3
Probability of VDC Implementation:		10%	90%	0%
Type of Improvement	Probaility of Occurrence of the Improvement	Probability of VDC as the cause of the Improvement		
		VDC1	VDC2	VDC3
Dramatic	81%	7%	93%	0%
Medium	19%	21%	79%	0%
Small	0%	0%	0%	0%

These results suggest that increasing the level of VDC implementation leads to a higher expected level of improvements.

11. Conclusions and Discussion

Using Bayes' Theorem implies that the data about project benefits are known, but the correct hypothesis about cause of outcomes is not. Therefore, the problem facing scientists is of the type "given the data (i.e., benefits expressed as project improvements), what is the probability that some specified hypothesis is true?" In our case we can conclude that for the available data (i.e., benefits), VDC implemented at level 2 is the most probable cause of project benefits, and that higher levels of VDC implementation lead to greater benefits. The application of Bayesian thinking to the study of the relationship between VDC implementation and benefits considering scarce relative evidence focuses on clarity of meaning rather than «rigor» in the narrow mathematical sense, Bayesian thinking can provide an alternative research approach to understand specific situations.

In the Bayesian approach we are using for construction management research, any probability assignment is necessarily "subjective" in the sense that it describes only a state of knowledge, and not anything that could be measured in a physical experiment. We expect that our Bayesian model will be updated in the future with new data about VDC implementation and benefits, and we cannot foresee whether there is any natural end to this process.

Since VDC modeling and particularly the model-based VDC analysis methods are evolving rapidly in theory, commercial tools and practice, we offer the approach of this paper as a point of departure to enhance the knowledge about the relationship between VDC implementation and benefits and potentially for other fields of Construction Management Research. Since Bayesian statistics is primarily a tool for evaluating relative evidence (Christensen et al, 2011), the research findings allow specifications of beliefs that can be updated continually.

VDC brings the project team together. Different team members part of the project organization have specific business objectives, including standards of their fields such as architecture, engineering, construction or finance, which, although different, can provide complementary perspectives for a project. Gathering data about project improvements where VDC organizational modeling have been applied in addition to product and process modeling (i.e., VDC at level 3) is the next logical recommended step to test the Bayesian approach to study the impact of VDC implementation in the construction industry.

Allowing practitioners and researchers to clearly understand the benefits of process and technology change such as VDC implementation will facilitate effective change and ultimately progress; in the case of VDC, by facilitating integration and multidisciplinary modeling and performance analysis to support explicit and public project management business objectives (see VDC definition in section 2). Effective implementation involves changing how buildings are designed and constructed and managed. Hence, this study of VDC implementation and benefits addresses a fundamental problem of construction management research.

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