Master of Science in Engineering

Key Indicators for Measuring BIM Collaboration Performance

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Abstract

Key Indicators for Measuring BIM Collaboration Performance

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Building Information Modelling (BIM) has been developed as an answer to the poor performances of the construction industry caused by its fragmentation. By gathering all project's actors on a central model, BIM is intended to facilitate a more integrated design, enhancing collaboration. However BIM achieves only partial benefits if not used collaboratively. Therefore project teams need to improve so manage their collaboration performance. Previous studies have enlighten the benefits of measuring performance with quantifiable metrics for a better management. Quantifiable metrics are more objectives, easier to understand and compare but have the disadvantage to require a qualitative interpretation to be used appropriately. Hence this research aims to investigate BIM collaboration performance in order to identify appropriate metrics to measure collaboration performance in a BIM environment.

A definition of collaboration performance as the collaboration process effectivity was used to retrieve 65 metrics from the literature. Then a survey supported by the Delphi method was conducted to evaluate them regarding two quality factors, appropriateness and suitability, to identify the ten most important metrics. A series of experts' interviews were performed to set up an interpretation of each metric. The results show that some categories of metrics appears more appropriate to measure BIM collaboration performance. Moreover the metrics present a non-linear relation with collaboration performance, contrary to what previous methods to evaluate BIM performances used.

This research contributes to enable BIM practitioners and researchers to measure and monitor teams' collaboration performance. It enables managers to identify critical situations and take correcting actions faster. Ultimately, it will contribute to the quantification of BIM collaboration performance and the comparison and identification of better BIM collaborative practices.

Keywords: BIM, Collaboration performance, Quantifiable metrics

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Chapter 1. Introduction

1.1 Research Background

Project performances depend not only on actors' expertise but also on how well they work together. For few decades, construction industry have been diagnosed with productivity, quality and other problems. It has been explained by the highly fragmented and specialized organization of the construction industry (Bresnen and Marshall, 2000). Indeed in most of countries, small and medium size companies and projects involving numerous still represent most of the construction market. To overcome these productivity problems, Building Information Modelling (BIM) has been thought and developed. BIM is a not only a computer-based model of a building (referred as Building Information Model, or BIM model), but rather a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a facility (Succar, 2013). By gathering all actors involved in the project around a central model, BIM allows AEC professionals to improve communication and achieve better project performances (Kam et al, 2013). Indeed BIM technologies enables simultaneous work by multiple disciplines, facilitating a more integrated design and construction process (Eastman et al., 2008). In other words researchers and practitioners have argued that BIM will enhances collaboration, reduce industry’s fragmentation (Homayouni et al, 2010; Succar, 2013; Singh et al., 2010). However it has been recognized early that BIM technologies alone would achieve only partial benefits if not used collaboratively (Estmann et al., 2008). BIM is not only an object or a set of technologies and software, but rather an activity, a new paradigm for the construction industry, involving new processes and policies. Stakeholders involved in a construction project using BIM should establish collaborative practices in tandem (Homayouni et al., 2010; Olatunji et al., 2015). This is the expression in BIM field of wider consensus on the importance of collaboration for project, and especially construction project, performances. Thus multiple applications to directly use and exchange BIM information have emerged to enhance project collaboration (Singh et al., 2010). Yet technology is not the exclusive solution. Therefore it is necessary for project teams using BIM to manage collaboration to improve their performance and also to identify best practices, processes and technologies, for the construction industry.

In management science it is acknowledged that measuring and monitoring performance are correlated with better results (Kam et al., 2013). Indeed measurement is the first step to understand situations and make changes. The principle “if you cannot measure it, you cannot manage it” is the motivation behind every measurement and monitoring management activities. This problematic have for example motivated many researches on evaluating

BIM performances. The development of BIM performance measurements is a pre-requisite for BIM performance improvement (Sebastian and Van Berlo, 2010; Succar et al., 2010). Similarly it is necessary to develop tool to measure collaboration performance (Thomson et al., 2007; Abdirad and Pishdad-Bozorgi, 2014). There are many ways to measure and monitor something. Metrics can be numeric, also referred as quantitative, or non-numeric, also referred as qualitative. They are also subjective or objective. Numeric metrics refer to every metrics using a number as information support. It is opposed to non-numeric metrics using other information support, such as text, categories. Subjective refers to metrics depending on a person's opinion whereas objective refers to metrics independent from the person's opinion.

Table 1.1 - Different categories of metrics.

	Subjective	**Objective**
Qualitative (non-numeric)	**Ex**: One's favorite BIM software. **Pros:** Capture complexity and subtlety. **Cons:** Difficult to capture and process; Depends of personal opinion; Difficult to compare.	**Ex:** The color of the Autodesk Revit's logo. **Pros:** Capture complexity and subtlety; Doesn't depend of personal opinion. **Cons:** Can be difficult to capture and process; Difficult to compare.
Quantitative (numeric)	**Ex:** One's opinion of the importance of BIM on a 1-9 scale. **Pros:** Easy to process and compare. **Cons:** Depends on personal opinion; Can be difficult to capture. Require more interpretation work.	**Ex:** The number of BIM researchers in SNUCEM. **Pros:** Easy to capture and process; Easy to compare. Doesn't depend of personal opinion. **Cons:** Require intensive interpretation work.

1.2 Problem Statement

BIM project teams need to manage so measure collaboration performance. Quantifiable metrics are quantitative and objectives. There are recognized as better for measuring and monitoring performance. They are easier to capture, to understand and compare (Du et al., 2014). Quantifiable metrics also need an interpretation basis to make sense, especially when related to such an abstract concept like, for example, collaboration performance. An individual not familiar with the metric cannot properly understand it without a minimum of interpretation like comparison with known situations or explanation of the meaning.

Therefore it is necessary to identify which quantifiable metrics can be used to measure collaboration performance in a BIM environment. Actually, as a matter of fact, it has been a growing concern in researches on evaluating BIM performances: subjective measures have been pointed out as sometimes un-reliable and BIM users need objective, so quantifiable metrics (Kam et al., 2013; Du et al, 2014). Furthermore it is necessary to make sure future users understand them properly, thus an explanation of each metric should be associated

1.3 Research Objectives and Scope

This research aims to investigate on quantifiable metrics for measuring BIM collaboration performance. It attempts to answer the questions of "which quantifiable metric can be used to measure collaboration performance in a BIM environment?" and "what meaning can be given to the identified metrics?".

Therefore the objectives are to identify quantifiable metrics to measure and monitor collaboration performance in BIM projects and to develop an interpretation for each metric to enable users to appropriately use them. It would enable BIM managers to quantifiably measure and monitor BIM teams' collaboration performance and then to compare BIM practices, methods and systems, in terms of collaboration performance. Thus this research would support the development and identification of better BIM collaboration practices, methods and systems through quantitative and objective comparative analysis.

The research focuses on teams working on construction projects using BIM tools and technologies. It is restricted to the design phase which is especially important for the development of the BIM model and is especially impacted by BIM and collaboration practices.

1.4 Research Methodology

For this research, a preliminary investigation on BIM performances evaluation methods was conducted. It was later extended to researches on BIM collaboration. The results revealed the necessity to set a definition of BIM collaboration performance. A multi-fields literature review was performed to identify existing definitions of the concept. After extracting several activities associated with collaboration, a collaboration process model was developed.

This model was used for the selection of candidate collaboration metrics. The metrics were selected from a pool of metric retrieved from BIM performance evaluations and others performance evaluations related to the construction industry. A survey supported by Delphi methodology was then developed to determine the most appropriate metrics and result analyzed by content validity analysis.

Delphi survey is a particularly useful method to answer a problematic when objective data are not available or unattainable. It differs from traditional survey by the use of multiple rounds and anonymous feedback to reach consensus. It allows more reliable results with a fewer number of experts (Hallowell and Gambatese, 2010). The survey was targeted to experts on BIM collaboration and BIM information management. A second survey of experts' opinions was conducted through expert interviews to determine and validate a simplified characterizations of each metric. As a result the research process can be defined in five steps as shown in Figure 1.1. The first step was to develop a definition of collaboration to define the framework of the research. The second step was to select a restricted number, about ten, of quantifiable metrics to measure BIM collaboration performance. The last step was to determine a first interpretation for each of the selected metrics.

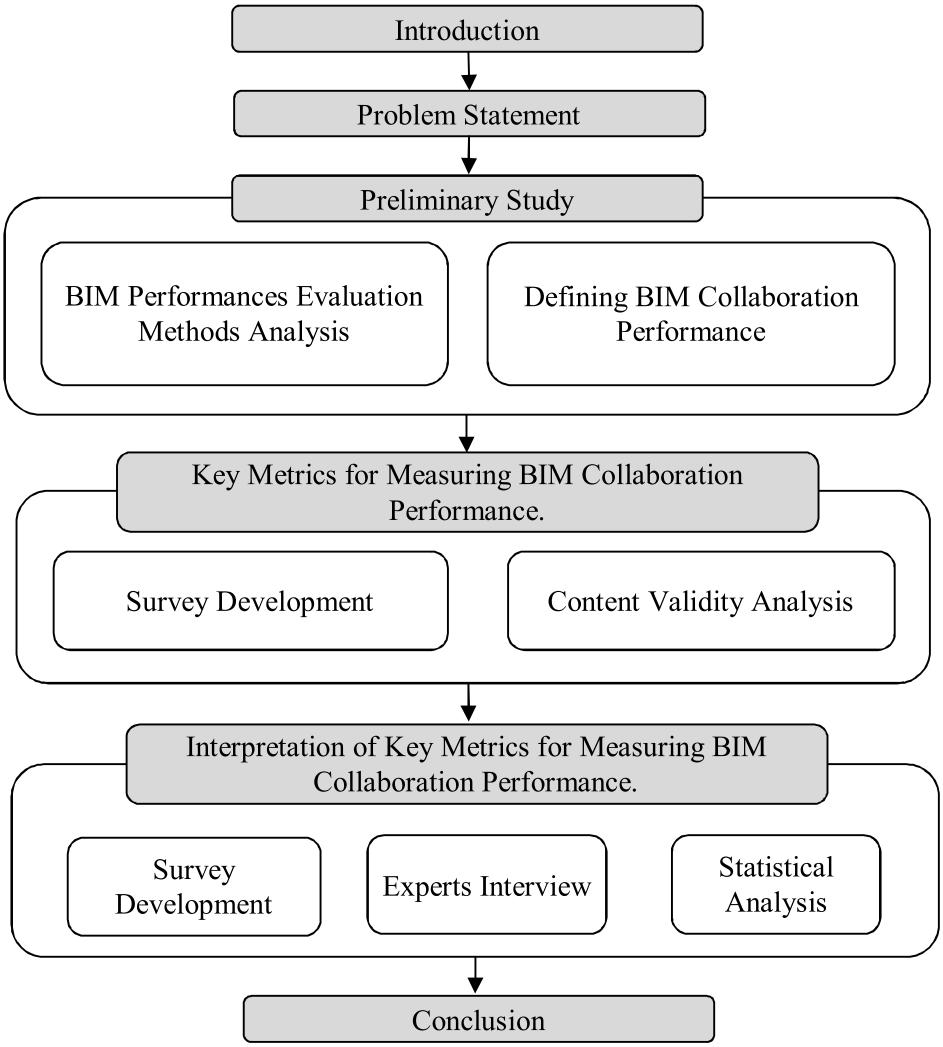


Figure 1.1 - Research Process

Chapter 2. Preliminary Study

This chapter deals with previous researches that attempted to study BIM collaboration. Many factors may influence BIM collaboration; yet previous researchers have focused mainly on collaboration system or organizational collaboration. Due to the importance of the collaborative dimension of BIM, some BIM performance evaluation methods have tried to include evaluation of collaboration in their frameworks considering mainly these two factors. Yet it appears that the difference of focus when studying BIM collaboration, come from the fact that what is collaboration and thus what is collaboration performance is rarely defined. Therefore this research performed a wide literature review on collaboration performance definition, extended from different academic fields other than construction engineering and management. Consequently the definition of collaboration performance used in this research is presented in this chapter.

2.1 Researches on BIM Collaboration

Previously, scholars and practitioners have widely acknowledged the new opportunities for collaboration that BIM introduces but also pointed out that it challenges organizations structure and methods and that determining the new process to achieve full performance is an issue (Eastman et al., 2008). Some researcher have studied the relationship between organizations' strategies and successful BIM implementation. Homayouni et al. (2010) have focused on *theoretical categories* of successful inter-organization collaboration, intending collaboration as a structure regrouping several organizations. *Theoretical categories* are those general factors identified as important for success. Results show that pursuing a collaborative environment is necessary for successful BIM implementation. While studying organizations' response to BIM implementation, Olatunji (2010) have underlined the importance of collaboration as a strategy to successfully adapt to BIM. Some other researcher have focused on collaborative systems for BIM, and their important characteristic for BIM collaboration. Shafiq et al. (2013) and Singh et al. (2011) studied the important system features for BIM collaboration. Shan et Sheng (2014) identified Critical Success Factors for BIM Collaboration. Somehow, the majority of the researches on BIM collaboration have focused on *how to* or *what to do* to enhance collaboration, from different perspectives (organizations structures, organizations strategies, systems features).

Collaboration being an important element of BIM it has been mentioned in some methods developed to evaluate BIM performances. As evaluating performances is key factor to properly manage and improve performances, many BIM Performances Evaluation Methods, also called BIM Maturity Evaluation Tools or BIM Assessment Methods have been developed through the years. Among these, about half tried to incorporate criteria related to collaboration. However their latent definition of collaboration differs. For example, in his BIM Maturity Matrix, Succar (2010) refers to level of trust, goodwill and respects which are success factors of collaboration. Gao (2011), refers to MEP coordination activity.

Table 2.1 - Existing BIM Evaluation Methods

Tool	ICMM	BIM Proficiency Matrix	BIM Software Evaluation Model	BIM Maturity Matrix	BIM Quickscan	CPIx BIM Assessment Form
Developer	**NIBS**	**IU**	**Ruiz**	**Succar**	**TNO**	**CPI**
Year	2007	2009	2009	2010	2010	2011
Criteria related to Collaboration				●		
Tool	VICO BIM Score	BIM Characterization Framework	BIM Owner Maturity Matrix	VDC Scorecard	bimScore	BIM Cloud Score
Developer	**VICO**	**Gao**	**CIC**	**CIFE**	**binSCORE**	**Du**
Year	2011	2011	2012	2013	2013	2014
Criteria related to Collaboration	●	●	●		●	●

Finally most of these research use non-quantifiable metrics for their evaluation and never more than three quantifiable metrics related to collaboration. This draws the two major differences between the present study and previous ones: it explicitly focus on collaboration performance and use quantifiable metrics.

One observation that can be conducted from the analysis of existing BIM Performance Evaluation Methods is that the difference in scopes objects of studies in researches related to BIM collaboration seems to come from a lack of definition of *what is* collaboration. In a more general approach, the construction literature seems to have many different understandings of collaboration. It also appears that sometimes *coordination* or *cooperation* are used interchangeably with collaboration. As explained by Mattessich and Monsey (1992) and Kvan (2000) these three terms can be understood as distinct level of the same concept, which is used in this research. The difficulty to find a consensus on a definition of BIM collaboration in the related literature, makes necessary to first establish such a definition. It is important for a better understanding of what is studied in the present research and as well to conduct the research.

2.2 Defining Collaboration Performance

Collaboration has been an important field of research not only for construction industry but also for other academic fields. Many efforts have been done to establish definitions of collaboration. Wood and Gray (1991) first established that collaboration occurs when a group of stakeholders engage in an interactive process to reach a common objective. Collaboration is the act of working together, or process of shared creation (Kvan, 2000). In an effort to synthesize the theories of collaboration, Thomson and Perry (2006) noticed that collaboration scholars revealed that collaboration is a process and should be studied as a process. Thomson et al. (2007) and Bedwell et al. (2012) insisted that measuring collaboration should consider the concept as a process and not an organization or an outcome. This approach, adopted in this research, conduct to define collaboration performance as the performance of the collaboration process. There are three major performances to evaluate a process:

- The effectiveness of the process which is the ability of the process to reach its intended results or objectives.
- The efficiency of the process which is the ratio between the resources (input) dedicated to the process and the results obtained (outcomes).
- The effectivity of the process, which means if the process is actually performed or not.

The effectivity pre-conditioned the other project performances. It is a measure of the existence of the process and therefore appears as the most appropriate to define collaboration performance. In this research collaboration performance is defined as the collaboration process effectivity. A process is a sequences of activities so the process effectivity can be measured by measuring, or controlling, the execution of the activities or steps defining this process, which means if the activities are performed or not. Therefore quantifiable metrics to measure collaboration performance are quantifiable metrics rendering the execution of the activities, and each of them, involved in the collaboration process. Quantifiable metrics for measuring BIM collaboration performance are quantifiable metrics related to BIM for measuring the BIM project team collaboration process effectivity.

Two problems can be objected to this approach:

- To what extend the execution of one step renders the execution of the overall process? It is probably impossible to assign an importance weight to any step because by definition of the process, all activities and steps are important.
- Does a metric render of the execution of one step only or is it influenced by other activities? And does it renders 100% of the execution of the activity?

These two questions are related to the problem of the relationship between the metrics selected based on the execution of a step and the overall effectivity. In other words it is related to the meaning of a metric to render an abstract concept performance. To minimize the uncertainties and inaccuracy, a five steps rigorous method is proposed:

1. To determine precisely the different activities or steps involved in the collaboration process.
2. To determine the importance of each activity's execution in the overall execution.
3. To identify metrics rendering the execution of each activity.
4. To check for each metrics if it is impacted by other activities and to determine to what extend each of these activity impact the metric.
5. To determine how much the metric actually captures the execution of the assigned activity.

The difficulty of this method is that it would require a lot of data that are not available and unattainable. Indeed further investigations and analysis of the collaboration process should first be performed. Then data should be collected to analyze the importance of each steps and activities and metrics should be identify and validated for each ones. More analysis should further be performed to identify the impact of each activities on each metrics and finally further investigations on the quality of each metric should be performed. All of these analysis will require data and iteration not yet available and attainable, mainly because it remains unknown yet which data to collect. Therefore in this research we propose an alternative approach to overcome the problem of unattainable data and build up a first step in the investigations towards a quantitative measurement of collaboration performance. This method is described as below:

1. To elaborate a simplified model of the collaboration process.
2. To identify a number of quantifiable metrics related to BIM
3. To assign one or many steps of the collaboration process to each metrics. If none the metric is eliminated.
4. To pursue and validate the selection by survey on expert's opinion, eliminating the inappropriate metrics. Experts' surveying is chosen because it has been proven as a steady method to provide results when data are not available.
5. To determine a raw characterization of the relationship between each metric and the overall concept of collaboration performance based on experts' understanding.

2.3 Developing Collaboration Process Model

To determine the activities involved in the collaboration process, eight publications from various fields have been analyzed. It includes one publication from Industrial Engineering (Neghab et al., 2015), one publication from Construction Engineering and Management (Kvan, 2000), two from Design Computing (Huang et al., 2001; Maher et al., 1998), three from Public Administration (Thomson et al., 2007; Woodland and Hutton, 2012; Ring and Van De Ven, 1994) and one from Behavioral Sciences (Wood and Gray, 1991). The analysis showed that collaboration process is an iterative and cyclical process rather than a linear process (Thomson and Perry, 2006; Kvan, 2000). Four general steps are proposed as components of this process: *Plan*, *Work*, *Question* and *Evaluate* as shown in Table 2.2.

Plan: The planning step is to make decisions (Woudland and Hutton, 2012) through negotiation (Huang et al., 2001; Maher et al., 1198; Thomson et al., 2007). The first is to define the problem (Wood and Gray, 1991; Thomson et al., 2007; Ring and Van De Ven, 1994) which ensure the purpose of collaboration and its outcomes (Kvan, 2000). It is also necessary to define the governing structure and rules of the collaboration (Kvan, 2000; Thomsom et al., 2007). Planning is the step during which actors define objectives, each ones' responsibility and tasks. Plan phase ends when every tasks are defined. It involves that tasks' objectives and evaluation criteria are defined.

Work: The collaboration process necessary involves a phase actors perform their own activities separately and execute the tasks defined in Plan phase (Neghab et al., 2015). The Work phase ends when tasks have reached their objectives or cannot be performed anymore because of missing information, data, or any problem.

Evaluate: Evaluation (Kvan 2000; Huang et al., 2001; Woodland and Hutton, 2012) or assessment (Ring and Van De Ven, 1994), is the phase during which actors merge and look at the work performed by each actor and judge it regarding the objectives and criteria defined in the Plan phase. It is a key phase of the collaboration process. The decision to pursue or stop the collaboration (if overall objectives are reached or not) is taken during this phase. The Evaluate phase ends when all the work performed has been evaluated. If overall objectives have been reached the collaboration process ends otherwise it means that more work has to be performed.

Question: The evaluation phase is a formal interaction phase, triggered by objective and pre-defined reasons. However some interactions between actors can be informal, due to the necessity to gather information, solve problems, and answer questions that were not planned. It is the Question phase during which actors exchange data (Neghab et al., 2015) ask advices (Maher et al., 1998) and dialogue (Woodland and Hutton, 2012). The Question phase can interrupt the Work Phase. After Question phase tasks and responsibilities may be renegotiated and redefined.

Table 2.2 - Main Steps of the Collaboration Process

	Neghab et al 2015	Kvan 2000	Huang et al., 2001	Maher et al., 1998
Plan		●	●	●
Evaluate	●	●	●	
Work	●	●	●	●
Question	●			●
	Thomson et al., 2007	**Woodland and Hutton, 2012**	**Ring and Van de Ven, 1994**	**Wood and Gray, 1991**
Plan	●	●	●	●
Evaluate		●	●	
Work		●	●	●
Question		●		

Knowing the phases involved in the collaboration process (Plan, Work, Question and Evaluate) and the structure of the process is enough to build a simplified model of the collaboration process as shown in Fig. 2.1.

This model is used as support for the definition of collaboration performance based on collaboration performance effectivity. It permits to identify appropriate metrics for measuring collaboration performance, those referring to one or many of the activities of the process. It will also support the understanding of experts, thus minimizing the confusion and guaranteeing more reliable results.

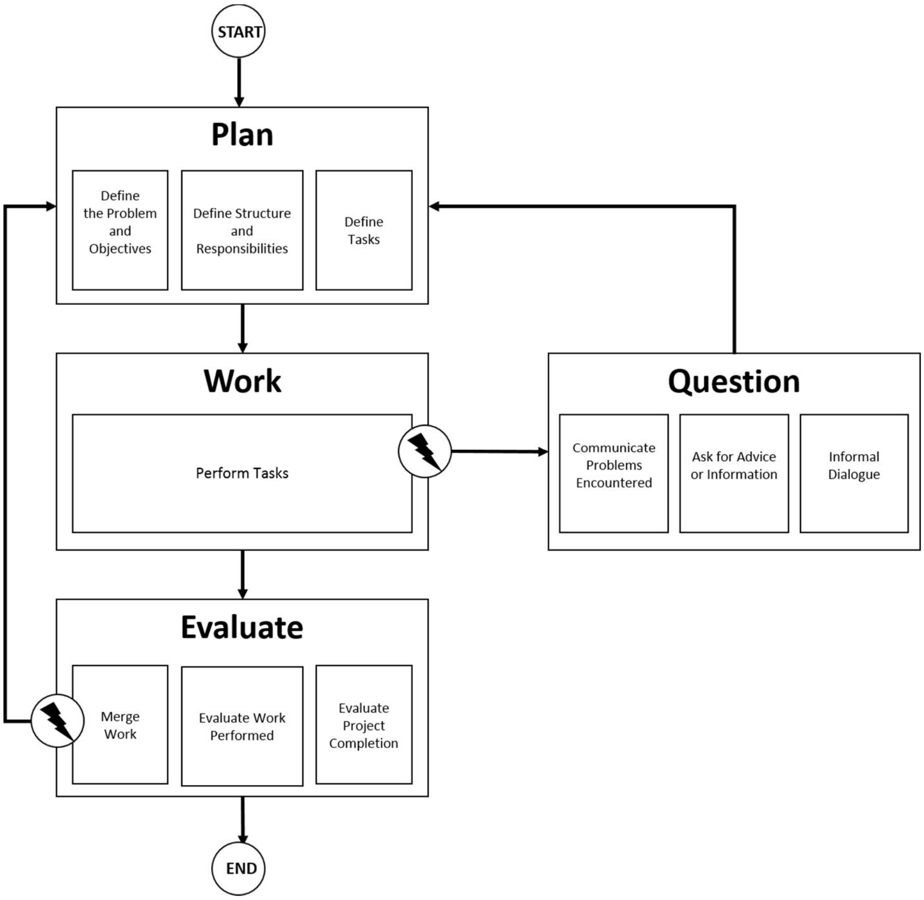


Figure 2.1 - Model of Collaboration Process

2.4 Summary

There were many researches about BIM and collaboration. Nonetheless, they focused on factors related to collaboration influencing BIM performances such as systems or organizations characteristics. The variety of perspectives can be explained by a lack of definition of the concept of collaboration adopted in these researches. Therefore, to measure collaboration performance it is first necessary to give it a definition. Collaboration has been identified as a process by many scholars. Thus collaboration performance is defined as the collaboration process effectivity and metrics to measure it as metrics rendering of the execution of the process' activities. A model of the collaboration process based on four steps – Plan, Work, Question and Evaluate - is adopted to help the identification of the appropriate metrics in this research.

Chapter 3. BIM Collaboration Metrics Development Framework

This chapter regards the metrics derived from the collaboration process model and how data were gathered and analyzed. In this research quantitative and objectives data, i.e. collected from real projects, were not available or not attainable. It was not possible to conduct a systematic analysis of real project conditions and data, thus the approach detailed previously was conducted. First a survey was developed through a systemic approach utilizing the collaboration process model proposed in this research. More than 500 measures related to BIM and construction projects were retrieved through an analysis of existing performance measurement methods. The collaboration process model was used to reduce the list to 65 metrics, submitted through survey to experts' judgment. To minimize the subjectivity of the survey method the Delphi methodology was adopted. The experts that were to participate in the survey were selected based on their expertise. The results were then analyzed using statistics tools and are presented in next chapter. Then a series of experts' interviews were conducted to elaborate and validate an interpretation of each selected metrics. The interpretation is based selected characteristic curve, chosen by experts' opinions.

3.1 Metrics Selection

In order to conduct this research, numerous metrics related to BIM and construction project were analyzed. Initially 558 indicators (quantifiable and non-quantifiable) were retrieved from 16 publications related to BIM and construction projects performance. BIM and construction projects performances related publications were considered as the most likely to provide metrics that can be capture in a BIM environment which is an important condition to measure BIM collaboration performance. Among these publications, existing BIM performance evaluation methods are especially important. Indeed they provide indicators already identify as representative of one or several aspects of BIM performance. Thus, an important effort was conducted to retrieve as most BIM performance evaluation methods as possible. 12 BIM performance evaluation methods were found and analyzed, including 3 with partial information only. To these methods, 4 noteworthy publication related to collaboration in construction were added. From these base pool of metrics, 209 were selected as quantifiable metrics as shown in Table 3.1.

Table 3.1 –BIM-related quantifiable metrics retrieved from literature.

Source	Du et al. 2014	Sebeastian and Van Berlo 2012	Ruiz 2009	Kam et al. 2013	bimSCORE 2012
Quantifiable Metrics	20	2	3	36	16
Source	Gao 2011	Senescu 2011	Abdirad and Pishdad-Bozorgi 2014	El-Asmar 2012	
Quantifiable Metrics	37	19	30	46	

The collaboration process model was then used to eliminate metrics not related to collaboration performance. It is part of the metrics' selection process as shown in Figure 3.1.

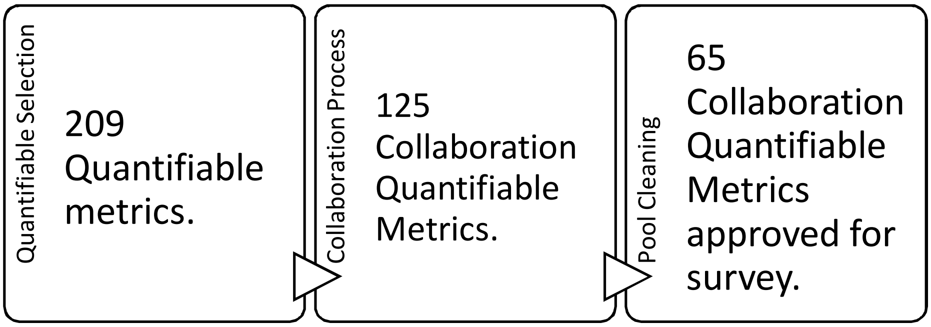


Figure 3.1 - Pre-selection process of metrics.

A metric is judged appropriate to measure collaboration performance if it can renders of the execution of one or many phase of the collaboration process. Experts' workgroup was identified as the most suitable method to obtain data. Indeed there were very few attainable experts of the collaboration process. Therefore the workgroup concerned two researchers involved in this study, selected for their understanding of the collaboration process model. It was asked to each person to fill an Excel sheet by assigning zero, one or many phases of the collaboration process to each of the 209 metrics. The differences in answers were then debated until consensus is reached. This selection process eliminated 125 metrics that couldn't fit the collaboration process model.

An analysis of this list of metrics revealed that some of them were very similar, yet different and that the differentiation could be applied to many others. Thus 28 metrics were suggested to complete the list and the metrics occurring multiple times were eliminated. The final list consist of 95 quantifiable metrics.

It was later submitted to an expert on BIM Information Management through an interview who suggested to reduce the list by regrouping frequency-based metrics and number-based metrics concerning the same object. The results of the interview also conducted to classify the metrics into 15 categories to enhance the ease of understanding of the list. The categories identified based on the analysis of the list are: *Objects and Systems, Level of Detail, Data, Warning and Clashes, Inconsistencies, Change Orders, Response Latency and Processing Time, Request for Information,* *Resubmittals, Design Iterations, Time Spent, Individuals, Costs, Information Transfers* and *Information Contents.* This categorization enable to clarify the meaning of each metric and therefore reduce the possible bias in the following study and enforce the reliability of the results. The final results is a list of 65 metrics as shown in Table 3.2

Table 3.2 - Pre-selected metrics for measuring collaboration performance.

Category	Metric
Objects and Systems	Number of objects in the model
	Number of objects created
	Number of objects removed
	Number of absolute objects number changes
	Average number of generic objects per assembly
	Number of modeled disciplinary systems
	Number of objects per sq.f. of the buildings
LoD	LoD in the 3D/4D model
	Model LOD per number of coordination meeting
Data	Number of break-down levels in the data structure
	Number of data entries
	Number of data changes
Warnings and Clashes	Number of clashes detected
	Number of clashes detected per object
	Number of clashes found per costs scope of work
	Number of warnings
	Criticality of warnings
	Number of hazards identified using 3D model
	Commitment reliability
Inconsistencies	Consistency of 3D model and 2D references
	Drawing coordination consistency
	Models' analytical reporting quality
	Internal consistency of design assumptions
	Discrepancies of each discipline's models
Change Orders	Change order rate
	Number of change orders
	Number of baseline revisions
	Number of scope changes approved
	Number of scope changes pending

Response Latency and Processing Time	Average change order processing time
	RFI processing time
	Average response latency
	Average speed of information transmission through a team
Request For Information	Number of RFIs
	RFI quantities in 2D vs 3D
	Percentage of on-time RFI to date
Resubmittals	Number of resubmittals
	Percentage of submittals approved
Design Iterations	Number of design iterations
	Number of iterations of BIM
	Number of local iterations
	Number of object modification
	Number of design alternatives modeled
Time Spent	Percentage of time working on BIM
	Time to creating BIM
	Time to managing BIM
	Time spent communicating
	Time spent communicating per person
Individuals	Number of persons engaged
	Number of individuals building BIM
	Number of individuals using BIM
	Number of individuals reviewing BIM
Costs	Cost of creating BIM
	Cost of managing BIM
Information Transfers	Number of value-adding information transfer between designers
	Number of face to face communications
	Number of virtual communications
	Number of planned interactions
	Number of unplanned interactions
	Number of time the model gets accessed
	Number of BIM enabled project-wide meeting
Information Contents	Number of statements about design trends
	Number of expressions of confusion
	Number of files upload per person
	Average amount of information in each transmission

This list was then submitted to experts' judgment through a Delphi survey. The survey aims to validate the appropriateness of the metrics to measure BIM collaboration performance. While analyzing the final list a second problem appeared: some metrics are not directly related to BIM. This research aims to identify metrics suitable for a BIM environment. Therefore it is necessary to evaluate the metrics regarding this criteria too.

3.2 Metrics Interpretation

Quantifiable metrics have many advantages over other metrics: they are objectives, easier to understand and compare, and easier to capture. A major disadvantage is that they require a sufficient understanding of their behavior to be used appropriately. This means that a qualitative interpretation must be associated with every quantifiable metrics. There are two type of interpretation possible: an *absolute interpretation* and a *comparative interpretation*.

The *absolute interpretation* means determining for each value of the metric a corresponding value of the performance measured. This approach triggers two problems. First for an abstract concept such as collaboration performance it implies to build a scale based on at least to reference values, which remains arbitrary. The second problem is the amount of data necessary to calculate such an interpretation.

The *comparative interpretation* means determining a comparison mechanism between two values, i.e. determining which one represent a higher performance. One solution is to build values class associated with a qualitative value. For example for metric’s value between x and y the performance is *low-medium-high.* While being less data intensive, this approach also requires some real data. Another solution is to determine the characteristic behavioral curve of the metric. This curve represent the approximated evolution of the performance measured. It enables to compare to values of the metrics without having quantitative data. This curve can be determined without being based on numeric value and later interpolated with real data.

Objectives data being not available ore attainable, this research used subjective data collected by survey to determine a characteristic curve for each metrics selected to measure BIM collaboration performance. This will enable future users, researchers or practitioners, to more correctly understand and interpret the metrics, reducing the risk of inconsistent results.

3.3 Surveys Development

Delphi survey was identified as the most appropriate method to collect the required information. Indeed it allows to reach a reliable results when objectives data are not available and only a small number of experts are available. A questionnaire was developed to further evaluate the characteristics of each metric. The evaluation criteria were derived from the results of the pre-selection process. Each metric is evaluated regarding its *appropriateness* and s*uitability.*

The *appropriateness* is the estimated ability of the metric to measure BIM collaboration performance. It was asked to the participant through the question “Is it an appropriate metric of BIM collaboration performance?”. The answer was measured by a 7-point Likert scale, 1 meaning not appropriate at all and 7 totally appropriate.

The *suitability* is the estimated ability of the metric to be captured in a BIM environment and to represent a BIM environment, both concept being closely related. It was asked to the participants through the question “Is it suitable for a BIM environment?”. The answer was measured by a 7-point Likert scale.

For each metric a comment was provided to reduce ambiguity and misunderstanding. The participants were explained the research, especially the used definition of BIM collaboration performance based on the collaboration process model. This approach aims to reduce the bias induced by the different definitions that experts can originally have.

The experts were evaluated and selected based on their experience of BIM collaboration and BIM information management. Thus the participants’ panel is constituted of 7 experts totalizing more than 90 BIM projects. Even though the number of experts can be perceived as low for a survey, the Delphi method allows such a small number (Hallowell and Gambatese, 2010). Multi-rounds and feedback being an important feature of the Delphi method, a second round survey was submitted. Feedback was provided by statistics information of the first round results: mean, median, standard deviation, first and third quartile. Participants were remembered their first round answer and asked to evaluate each metric a second time. The overall survey process is presented in Figure 3.2.

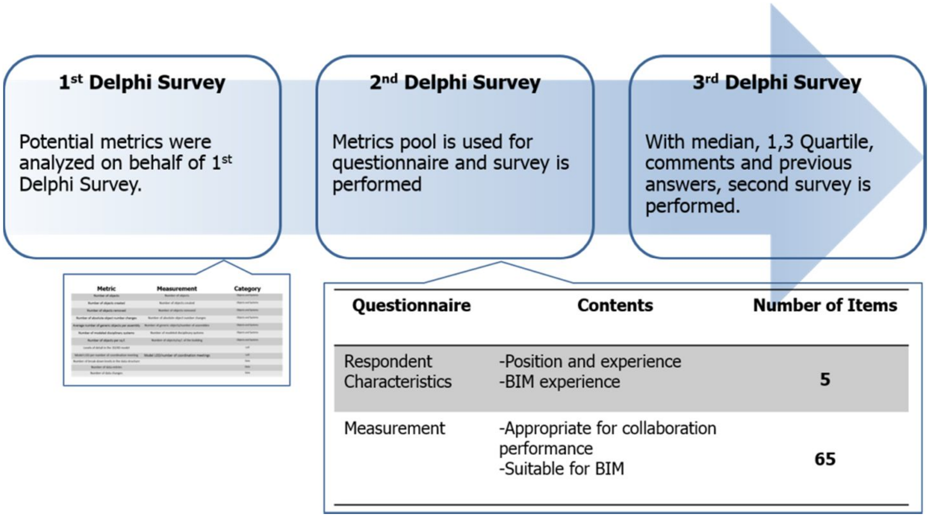
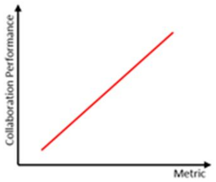
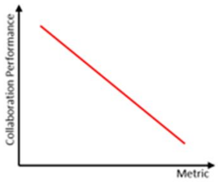
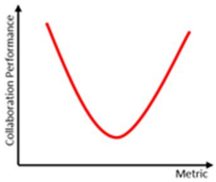
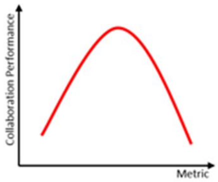
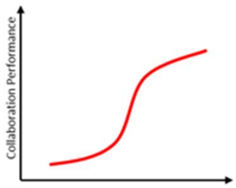
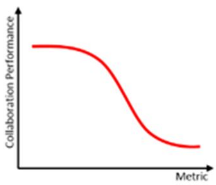
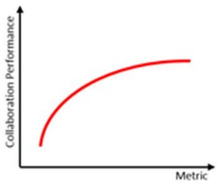


Figure 3.2 - Overview of the 1st Delphi survey process

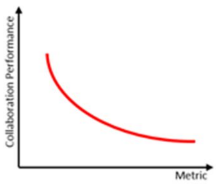
A second survey conducted through expert interviews was developed based on the results of the first survey. The metrics identified as most appropriate to measure collaboration performance in a BIM environment were used as the metric pool for the second survey. The objective of the second survey is to determine for each submitted metric a characteristic curve, representing the relation between the metric and collaboration performance. Ten different curves are proposed. They were selected based on their ability to represent different behaviors.

Table 3.3 - Proposed curves.

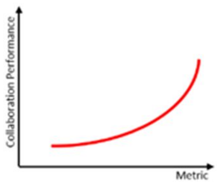
Curve	Comment
	This curve represents a linear-positive relationship: collaboration performance is positively proportional to the metric.
	This curve represents a linear-negative relationship: collaboration performance is negatively proportional to the metric.
	This curve represents a “U” or “V” shaped relationship: collaboration performance first decreases then increases.
	This curve represents a reversed “U” or “n” relationship: collaboration performance first increases then decreases.
	This curve represents a “S”-shaped relationship: collaboration performance first slowly increases, then quickly increases and then go back to slow growth.
	This curve represents a reversed “S” relationship: collaboration performance first slowly decreases, then quickly decreases and the go back to slow decrease.



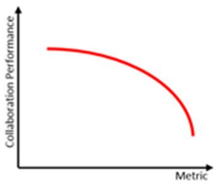
This curve represents a growing, stabilizing relationship: collaboration performance first increases quickly then more and more slowly.



This curve represents a decreasing, stabilizing relationship: collaboration performance first decreases quickly then more and more slowly.



This curve represents a decreasing, stabilizing relationship: collaboration performance first decreases quickly then more and more slowly.



This curve represents a growing exponential relationship: collaboration performance first increases slowly then faster and faster.

The participants were explained in detail the concept of collaboration and the definition of collaboration performance utilized in this research. They were then asked to give their opinion on each metric and to choose the curve they judge the most appropriate and to explain their decision.

3.4 Results Analysis

As the data for this research were collected from survey, the results were compared using content analysis. For each metric we define the criticality as the appropriateness multiplied by the suitability. A high criticality means that a metric is well related to BIM environment and appropriate to measure collaboration performance.

$$\boldsymbol{Criticality} = \boldsymbol{Appropriateness} * \boldsymbol{Suitability} \quad \textbf{(}\text{Equation 1)}$$

The results are analyzed with the following criteria: Mean, Standard Deviation, and Adapted Content Validity Ratio. The content validity ratio can be used to assess a content's validity (Lawshe, 1975). Content validity ratio measure the degree of conformity to importance and can be used as a measure of validity (Lawshe, 1975).

$$\boldsymbol{CVR} = \frac{\boldsymbol{n_e} - \boldsymbol{N}/_{\boldsymbol{2}}}{\boldsymbol{N}/_{\boldsymbol{2}}} \quad \text{(Equation 2)}$$

With $\boldsymbol{n_e}$: Number of panelist indicating "essential", and $\boldsymbol{N}$: Total number of panelists. Thus we propose the Adapted Content Validity Ratio:

$$\boldsymbol{ACVR} = \frac{\boldsymbol{n_c} - \boldsymbol{N}/_{\boldsymbol{2}}}{\boldsymbol{N}/_{\boldsymbol{2}}} \quad \textbf{(}\text{Equation 3)}$$

With $\boldsymbol{n_c}$: Number of panelist indicating criticality over 30, and $\boldsymbol{N}$: Total number of panelists. Table... indicates the minimal value of CVR depending on the number of panelists. In this research, the number of panelists is 7 so the minimum value of ACVR is 0.71. For each metric with an ACVR over 0.71, the metric can be determined as being valid.

Table 3.4 - Minimal values for Adapted Content Validity Ratio.

Number of panelists	**Minimal ACVR value**
5	0.99
10	0.62
15	0.49
20	0.42

25	0.37
30	0.33
35	0.31

3.5 Summary

This research retrieved 65 metrics using the collaboration process model developed in the preliminary study. The analysis of the metric list showed that is necessary to use two criteria to evaluate them: *appropriateness* for measuring collaboration performance and *suitability* to a BIM environment. An interpretation based on a characteristic curve was identified as an appropriate compromise between accuracy and feasibility. Ten characteristic curves were selected to characterize each metric. A first survey supported by Delphi methodology was developed based on the 65 metrics and the evaluation criteria. A second survey is developed using the ten characteristic curves. The participants to the survey were selected based on their expertise of BIM collaboration and BIM information management.

Chapter 4. Key Metrics Results

This chapter discusses the results of the survey and how they were analyzed. First the results of the survey were validated using Convergence, Agreement and Variation. Then correlation analysis was used to validate the importance of using to evaluation factors. Then metrics' criticality was analyzed to determine the most appropriate metrics. Finally second survey results were analyzed to assess the characteristic curve of each metric. It was found that 4 primary metrics could be validated using ACVR and 6 secondary metrics using a cross-comparison between a one rank lower ACVR and high criticality. The results of experts' interviews showed that a linear interpretation shouldn't be assumed for these metrics.

4.1 Survey Results Validation

Total of seven specialists answered the survey. The survey targeted experts on BIM information management and BIM collaboration. They were selected based on their experience with BIM and the final panel totalize more than 90 BIM projects. The survey were distributed through email and the participants had to respond to the questions online (Google Forms). The first round was conducted for three weeks and the second round as well. The results were then processed for analysis.

The validity of survey answers is analyzed using correlation coefficient (Correl coefficient and Pearson product-moment correlation coefficient), Convergence, Agreement and Variation.

Correl Coefficient:

$$Correl(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2(y-\bar{y})^2}} \quad \text{(Equation 4)}$$

Pearson Product-Moment Correlation Coefficient:

$$\rho(X,Y) = \frac{cov(X,Y)}{\sigma_x\sigma_y} \quad \text{(Equation 5)}$$

With: $\bar{x}$ is the average of X, cov(X,Y) is the covariance of X and Y, σ_x the standard deviation of X. For both coefficients 0 indicates that there is no correlation between the two variables X and Y, where as an absolute value of 1 indicates a perfect linear relation. Fig. 4.1 and Fig. 4.2 show the distribution of answers to the first survey in rounds 1 and 2 and the correlation between the first (appropriateness) and second (suitability) question. Table 4.1 shows the correlation coefficients for 1st and 2nd rounds.

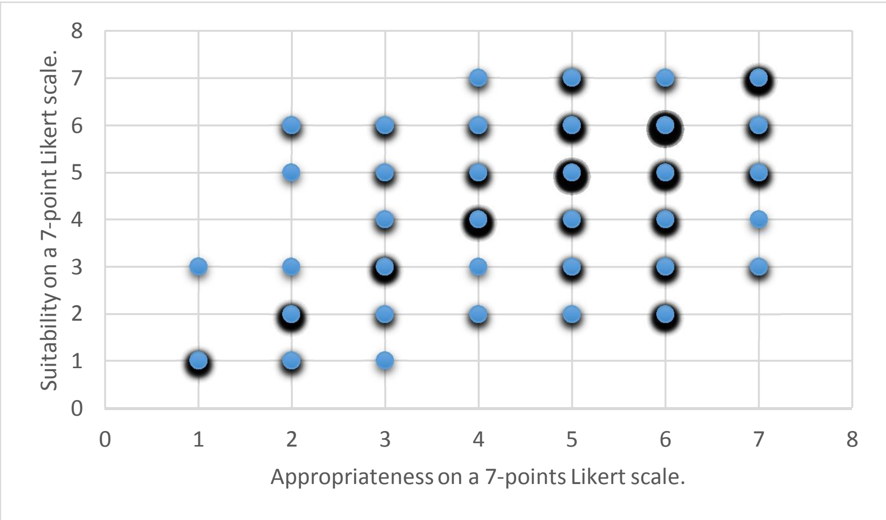


Figure 4.1 - Distribution of 1st round survey's answers.

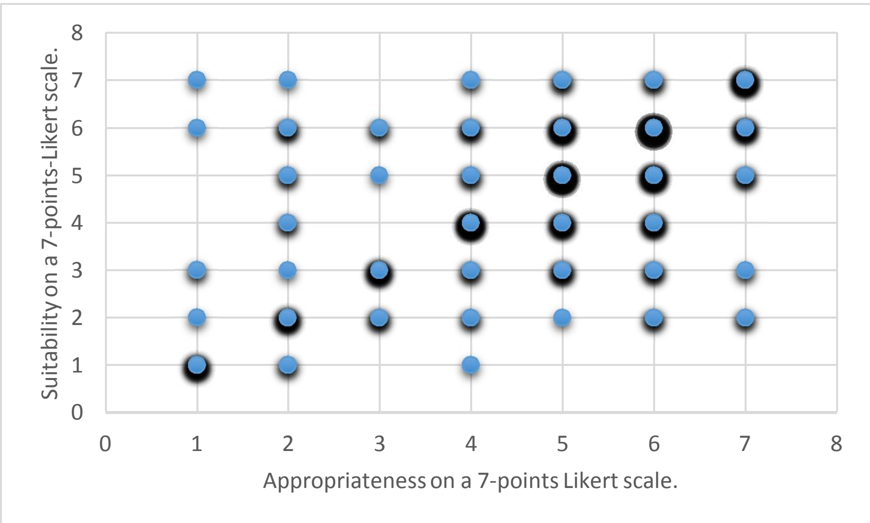


Figure 4.2 - Distribution of 2nd round survey's answers.

Table 4.1 - Correlation between answers to questions 1 and 2.

	Round 1		Round 2	
	Correl Coefficient	PPMC Coefficient	Correl Coefficient	PPMC Coefficient
Participant 1	0.046	0.046	0.272	0.272
Participant 2	0.286	0.286	0.341	0.341
Participant 3	0.722	0.723	0.820	0.820
Participant 4	0.994	0.994	0.994	0.994
Participant 5	0.521	0.521	0.218	0.218
Participant 6	1.000	1.000	1.000	1.000
Participant 7	0.902	0.902	0.902	0.902
All	0.616	0.614	0.649	0.649

Fig. 4.1 and Fig. 4.2 show that almost every possible answer were used by the participants. The coefficients of correlation between all participants' answers to question 1 and 2 are above 0.6. but below 0.8, indicating a non-independent relation but uncorrelated enough to justify the use of these two parameters (appropriateness and suitability). Moreover some participants may have a high correlation in their answers (>0.9) but others have a very low one (<0.1) as shown in Table 4.1. It is considered as sufficient to demonstrate the usefulness of having two different questions to evaluate both the appropriateness and suitability and obtain more reliable results.

The validity of Delphi technique can be evaluated using the degree of convergence and agreement (Lee et al., 2001). A Convergence degree close to 0 and an Agreement degree close to 1 indicate that the answers to the question are valid.

$$Convergence = \frac{Q_3 - Q_1}{2} \quad \text{(Equation 6)}$$

$$Agreement = 1 - \frac{Q_3 - Q_1}{Mdn} \quad \text{(Equation 7)}$$

With Q_3 and Q_1 are respectively the third and first quartile and Mdn is the median of the dataset. The Coefficient of Variation can be used to evaluate the stability of the answers in multi-rounds survey. A Coefficient of Variation below 0.5 means that no additional survey are necessary, a value between 0.5 and 0.8 means that the answers can be considered relatively stable and above 0.8 additional survey are necessary. Table 4.2 shows the convergence, agreement and variation for question 1 and 2.

Table 4.2 - Validity of survey results.

	Question 1						**Question 2**					
	Convergence		Agreement		Variation		Convergence		Agreement		Variation	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Mean	0.77	0.67	0.68	0.70	0.28	0.28	0.82	0.75	0.61	0.67	0.33	0.30
SD	0.47	0.40	0.24	0.29	0.14	0.14	0.40	0.38	0.29	0.23	0.13	0.14
Min	0.00	0.00	-0.17	-1.00	0.08	0.08	0.00	0.00	-0.25	0.00	0.11	0.10
Max	2.25	2.00	1.00	1.00	0.65	0.70	1.75	1.75	1.00	1.00	0.62	0.63

As shown in Table 4.2, the stability of the answers is good: under 0.8 for every metric with an average 0.28. Agreement is near 0.7 for both questions which is good. With a mean near 0.65, convergence remains a bit high but is very good for many metrics (degree of convergence of 0). On overall, the validity of survey results is ensured.

4.2 Key Metrics Identification

The metrics are analyzed regarding their criticality as explained previously. Thus the metrics both appropriate for measuring collaboration performance and for a BIM environment can be identified. Table 4.3 shows that there are difference in rankings regarding mean appropriateness and mean suitability. Some metrics such as *Time spent communicating* are ranked with a top appropriateness (rank 4) but low suitability (rank 42). On the contrary the *Number of break-down levels in the data structure* ranks 11 in suitability but 42 in appropriateness. This underlines the importance to assess both criteria when selecting metrics to measure BIM collaboration performance.

Four metrics are validated using the Adapted Content Validity Ratio: *Drawing coordination consistency* (Number of inconsistencies in drawings), *RFI processing time*, *Number of time the model gets accessed* and *Number of BIM enabled project-wide meetings*.

More metrics can be suggested based on cross-comparison between

ACVR and criticality. Indeed 13 metrics have an ACVR above 43, which would sufficient with more participants to the survey. These 13 metrics can be analyzed through the mean criticality which is a strong indicator of the quality of the metrics to measure BIM collaboration performance. Therefore 6 secondary metrics are selected for having an ACVR above 0.43 and a criticality above 32.66, two-thirds of the maximum criticality 49. These metrics are *Discrepancies of each discipline's models* (number of discrepancies/number of objects), *Change order rate*, *Average change order processing time*, *Average response latency*, *Number of value-adding information transfer between designers* and *Number of expressions of confusion*.

Table 4.3 - Selection of key metrics.

	Appropriateness		**Suitability**		**Criticality**		**ACVR**	
	Mean	**Rank**	**Mean**	**Rank**	**Mean**	**Rank**	**Value**	**Rank**
Drawing Coordination Consistency	5.86	9	5.86	4	34.57	5	0.71	2
RFI Processing Time	6.00	4	5.43	13	33.14	9	0.71	2
Number of time the model gets accessed	5.57	16	6.00	2	34.71	3	0.71	2
Number of BIM enabled project-wide meetings	6.43	1	6.29	1	40.71	1	1.00	1
Discrepancies of each discipline's models	6.14	3	5.57	11	34.71	3	0.43	5
Change order rate	6.00	4	5.43	13	32.86	10	0.43	5
Average change order processing time	6.29	2	5.71	7	36.00	2	0.43	5
Average response latency	6.00	4	5.43	13	32.86	10	0.43	5
Number of value-adding information transfer between designers	5.57	16	5.86	4	33.29	8	0.43	5
Number of expressions of confusion	5.86	9	5.71	7	33.71	7	0.43	5

The ten selected metrics, primary and secondary, represent 5 categories: Inconsistencies, *Change Orders, Response Latency & Processing Time, Information Transfers and Information Contents*. With the analysis of each category by mean appropriateness, suitability and criticality as shown in Table 4.4, it suggests that *Response Latency & Processing Time, Information Transfers and Inconsistencies* are the most important in the development of metrics to measure BIM collaboration performance. Surprisingly metrics related to Objects and Systems, the basis of BIM models, and Warnings and Clashes, one major feature of BIM technologies, didn't get a good scoring.

Table 4.4 - Analysis of categories.

	Appropriateness		**Suitability**		**Criticality**		**ACVR**	
	Mean	**Rank**	**Mean**	**Rank**	**Mean**	**Rank**	**Mean**	**Rank**
Objects & Systems	3.53	15	3.78	15	15.53	15	-0.59	15
Level of Details	4.00	14	4.07	14	18.86	13	-0.57	13
Data	5.09	8	5.14	5	27.00	8	0.24	3
Warning & Clashes	4.59	11	4.25	12	21.04	11	-0.31	10
Inconsistencies	5.51	3	5.49	2	31.28	2	0.14	4
Change Orders	5.40	4	4.97	8	27.97	4	0.03	6
Response Latency & Processing Time	5.97	1	5.57	1	33.50	1	0.50	1
Requests For Information	4.90	9	4.43	10	22.48	10	-0.52	12
Resubmittals	4.14	13	4.08	13	18.64	14	-0.57	13
Design Iterations	5.32	5	5.12	6	27.77	6	-0.09	7
Time Spent	5.32	5	5.06	7	27.23	7	-0.09	7
Individuals	5.18	7	5.25	4	27.93	5	0.14	5
Costs	4.29	12	4.43	10	20.58	12	-0.14	9
Information Transfers	5.57	2	5.38	3	31.09	3	0.35	2
Information Contents	4.82	10	4.89	9	24.57	9	-0.36	11

4.3 Key Metrics Interpretation

Five experts interview were conducted over one week. The experts are members of CM and architecture, Korean and international companies occupying BIM management and modelling positions. The survey to select the characteristic curve for each metric was conducted during these interviews. The participants were explained the concept of collaboration performance used in this research as well as the different selected metrics and proposed curves. They were then asked to give their opinion and choose a curve. The results, as shown below, indicate that experts couldn't decide for one specific curve but rather 2 or 3 of them for each metric. Moreover, following experts recommendation, the metrics were regrouped into 3 categories similar to the previous ones: Inconsistencies, Response Time and Information Transfers.

Category 1 – Inconsistencies:

Drawing coordination consistency: Measured by the number of inconsistencies (missing information, wrong values, others). It was indicated than the type of inconsistency could be important and should be defined, especially when referring to computer-based (and BIM) design without paper drawings. The most appropriate would be the absolute number rather than frequency or cumulated number over a period. The curve associated is decreasing, the more inconsistency the harder the work/the collaboration until it exceed a work limit that burdens the collaboration performance. Thus the suggested shapes are 6 or 10.

Change order rate: Experts reported that the origin (client, contractor, others) of change order could be affecting. It was also triggered that the change order characteristics certainly impact on clashes, consistency and processing time, making it an important measure of collaboration quality and burden. The suggested shape are decreasing shapes (6, 8 or 10). Experts especially considered the importance of a workload limit: a range of values indicating a fast decrease of performances.

Discrepancies of each discipline's models: It was unanimously considered similar to *Drawing coordination consistency* (number of inconsistencies) by experts, suggesting a fusion between these two metrics.

Number of expressions of confusion: A decreasing shape is suggested (curves 6 or 10).

Category 2 – Response Time:

Average change order processing time: It was triggered by all experts that the processing time depends on the efficiency of communication process, communication tools and organizational structure which are acknowledged as important factor of collaboration performance. Thus it validates the importance of this and similar metrics to measure collaboration performance and compare practices. It was suggested that a decreasing shape, preferred curves 6 or 10, is the most appropriate.

Average response latency: Similarly to *Average change order processing time* it was underlined by experts that the communication tools, process and organizational structure might impact this metric. It confirms it as an interesting candidate for measuring collaboration performance and comparing practices, as suggested by experts. A decreasing shape, curves 6 or 8, is suggested as most appropriate.

RFI processing time: Decreasing shapes are suggested as the most appropriate. It is explained by experts that the number of issues solved would impact the human resources and success, underlining the importance of the workload limit. Curves 6 and 10 would be the most appropriate.

Category 3 – Information Transfers:

Number of time the model get accessed: It was suggested that the reasons of access (modeling, analyzing, and checking) could impact the shape of the relation. However an increasing shape, curves 5, 7 or 9, were judged as the most appropriate.

Number of BIM enabled project-wide meetings: Similarly it was suggested that the type of meeting (regular coordination, RFI, change order, information checking, learning), might change the graph shape. The number of meeting can improve the collaboration performance but meetings can also means confusion or issues needing to be solved. Therefore it was suggested an increasing shape with a workload limit such as curve 5 or 7.

Number of value-adding information transfer between designers: An increasing shape was suggested (curve 5,7 or 9). It was reported that while using an integrated model the value-adding information transfers might be harder to track since most of information are exchanged through the model without necessary targeting a specific actor. Consequently, specific tools to track these in integrated models should be developed.

Complementary to the comments on metrics interpretation and characteristic curves, several points were triggered by experts, as synthetized below. The quantified graph or curve, probably strongly depends on environment characteristics such as project characteristics, team characteristic, organizational characteristics, communication processes and technologies. It also probably depends on the phase of the project, since the efforts are not equally shared on time. Such a dependence is strongly expected since these are all parameters acknowledged as influencing the collaboration and project performances. It is one of the main interests of measuring and monitoring collaboration performance: comparing the different performances of different practices and tools to identify the most performing ones. Moreover the different metrics are likely to be interconnected and the relation between those have to be investigated.

The second comment is about how the metrics could be used. It was noticed by experts that there is certainly difference between reality and expectations (theory) when collecting data. This is one purpose, since it allows practitioners and researchers to discover some new findings from and about the project. It was considered by the interviewees as one of the main motivations for researches on quantifiable metrics. The results of collecting data could have meaning for the specific project only, but while accumulating then on many projects, some common findings for BIM collaboration could be found.

The last point concerns the specificity of a BIM environment. It was reported that BIM strongly affect how some metrics are generated, which confirms its value to improve collaboration performance, but also defined. For example drawing inconsistencies in a fully integrated BIM environment do not make sense. Therefore the metrics should be defined carefully for a BIM environment, which validate the strategy followed in this research.

4.4 Discussion

The analysis of correlation between *appropriateness* and *suitability* showed that the distinction has to be made and is important to find metrics specific and appropriate for BIM environment. Indeed the correlation coefficient measured was slightly above 0.6, indicating a just above average correlation. This is significantly different from a high correlation since all of the metrics submitted to experts through survey were derived from the literature related to BIM and CEM. This shows, as it was confirmed by experts interviewed, that researcher working on the development of metrics to measure and evaluate projects, organization, technologies, team or others performances should carefully assess the specificity of the metrics for a BIM environment. Indeed the characteristics of a BIM environment, make the evolution, interpretation and meanings of metrics different than in a traditional environment. Therefore the performance measurement practices in this new BIM environment should differ from the ones used in a traditional environment.

Further analysis revealed that Response Time, Information Transfers and Inconsistencies are the categories the most appropriate to measure BIM collaboration performance. Therefore future development of metrics to measure BIM collaboration should likely focus on these categories. Similarly, the analysis per collaboration process phases showed that Question and Evaluate are the most important phase, with a respective mean criticality of 27.20 and 26.91. Planning got 25.39 and Individual Work 21.79. The lower score of Individual Work phase isn't surprising since this phase is not specifically unique to the collaboration process. But the one of Planning, important in structuring the collaboration and differentiating it from cooperation and coordination, could indicate that new metrics, more adapted, should be developed based on the identified category to evaluate this phase more appropriately.

The experts' interviews revealed that metrics don't follow a linear shape. It enlightens the importance a plateau, or shift, effect, due to a workload limit, that manager should be aware off. Indeed for every metrics it is expected that there is range of values related to strong performance changes beyond which the changes are more flattened. This has important implications for collaboration performance management. In case of a shape of curve 5 (respectively 6) it means for an increasing relation (decreasing) that there is value below (above) which the performance indicating is quickly deteriorating and is then stable. Thus managers should look carefully not going below (above) this shift value because improving performance will be complicated and effort intensive. Similarly being comfortably above (below) this value guarantee that collaboration performance is stably high. In case of curve 7 (resp. 8) it means that low values indicates a quickly deteriorating (improving) performance. In the flattened range of value not too much should be put into improving these performance metrics because it is related to minor performance improve. For curve 8 it means that once high value reached it will be difficult to change the trend and improve performance, so all the attention should be put to stay in the unstable but improvable quickly changing zone. The same consideration can be added to shapes 9 and 10. On overall this research shows that these metrics can be used to monitor and detect the shift zone related to drop (or quick improvement) in collaboration performance. Collaboration performance being an upfront indicator of project performances, it is therefore possible to detect earlier some problematic situations.

The non-linearity of the relations, or curves, has another important consequence for BIM Performances Evaluation Methods. Indeed most of them use scoring methods based on weighted factors, involving a strictly linear relation between the metrics value and the overall score or performance. The results of this research suggests that such an approach is not appropriate and could lead to inaccurate performances measurements and ultimately inappropriate management practices. However all the metrics were identified as following an increasing or decreasing curve, suggesting that it is already possible to use them to compare and to classify the different practices.

Finally by accumulating the data from many projects it would be possible to discover some common findings about BIM collaboration, such as the characteristic curves and their quantification. A better understanding of these will unable to compare communication processes, communication tools, organizational structure and BIM technologies regarding collaboration performance and therefore to identify the best performing ones.

4.5 Summary

A Delphi survey was conducted with seven experts to select the most appropriate metrics to measure collaboration performance in a BIM environment. The analysis of results using correlation, agreement and stability coefficient showed that results are valid. Content validity analysis was used to retrieve 10 metrics. A series of five experts' interviews was then performed to build an interpretation of each metric. It was found that choosing a specific characteristic curve was impossible due to the importance of environment factors such as project characteristic, communication tools and process but that it is possible to choose between decreasing or increasing trend. Moreover the importance of change in variation rate (workload limit) has been revealed as a key concern and findings.

Chapter 5. Conclusion

5.1 Research Summary

This research has developed a definition of BIM collaboration performance based on the effectivity of the collaboration process measured in a BIM environment. This definition was set to overcome the limitation of previous researches which were diverging their scope and concepts. A general collaboration process model was developed to support the definition of identification of potential metrics to measure BIM collaboration performance.

Using the definition set in this research, a Delphi survey was conducted to identify the most appropriate metrics using *appropriateness* and *suitability*. The analysis of agreement, convergence and stability, confirmed the validity of the results. Ten metrics were identified using content validity and criticality analysis. These metrics are *Drawing coordination consistency* (Number of inconsistencies in drawings), *RFI processing time*, *Number of time the model gets accessed* and *Number of BIM enabled project-wide meetings*, *Discrepancies of each discipline's models* (number of discrepancies/number of objects), *Change order rate*, *Average change order processing time*, *Average* *response latency*, *Number of value-adding information transfer between designers* and *Number of expressions of confusion*. Following the results of expert interviews, *Drawing coordination consistency* and *Discrepancies of each discipline's models* are merged into one metrics: *Number of inconsistencies* (missing data, wrong value, others).

A second survey was intended to be performed during experts' interviews to identify a characteristic curve for each selected metrics. The experts unanimously explained they couldn't choose a specific curve but rather a trend, increasing or decreasing curves. Therefore *Response Time* metrics follow decreasing curve, Inconsistencies metrics follow decreasing curves and Information Transfers metrics follow increasing curves. Interviews furthermore revealed that non-linear curves were the most likely, suggesting that the metrics identified in this research can be already be used to manage BIM teams' collaboration performance and compare practices and tools.

Finally as it has been discussed in previous part, experts interviewed confirmed that quantitative data should be collected and accumulated from real projects. It will allow to discover some common findings about BIM collaboration, leading to better performance measurement, tools and practices comparisons.

5.2 Contributions

This research enables practitioners and researchers and measure and monitor collaboration performance of BIM project teams. It identifies the existence of workload limits related to quick collaboration performance deterioration which impact strongly negatively project performances. As a first contribution this research proposes a method, as a series of 9 metrics, to monitor project and detect these problematic situations. While a quantitative description is not yet available due to data limitation it enables managers to know which metrics to monitor and then use their experience and expertise to identify the problematic situations and adopt corrective actions.

This research also revealed the importance to carefully assess the metrics used to measures performances in BIM projects. Indeed it has been found first that some metrics usually identified as appropriate for performance assessment can be inappropriate in a BIM environment. Secondly the characteristic of the project environment has an important impact on the meaning and interpretation of the metrics. BIM being an important shift from traditional practices, usual metrics shouldn't be used similarly in both environments. Thirdly, this research revealed the non-linearity of relation between metrics and performance. This challenges the assumptions used in most of previous BIM performances evaluation methods based on weighted scores, so linear relations.

Furthermore this research will allow practitioners and researchers to collect the appropriate data to further analyze the BIM project collaboration dynamics. Later on it would be utilized to compare the communication process, communication tools, organizational structure, BIM technologies and identify those leading to the highest collaboration performance. Better collaboration performances being associated to better project performances such as quality, schedule, costs, innovation, and participants′ satisfaction it would ultimately lead to better construction projects, construction companies, and construction industry performance.

Finally this research also contributes to identify the most promising direction to develop metrics to measure BIM-related performances. Thus it underlines the importance of developing BIM specific metrics, assessed as suitable and representative of BIM otherwise interpretation so utilization could be challenged. In the domain of BIM collaboration performance, it identifies *Inconsistencies*, *Processing Times*, and *Information Transfers* as the most promising category. It also enlightens the importance if the Plan, Question and Evaluate phase of the collaboration process and suggest that further development should focus on these phases.

5.3 Limitations and Further Research

The first limitation is regarding survey results. While analysis using Agreement, Convergence and Variation coefficient confirmed the validity of the results, the high correlation between *appropriateness* and *suitability* in some participants answer might have hidden more information and potential findings. Therefore re-conducting a similar survey with more participants could limit the effect of some highly correlated answers, and eventually bring more information and findings.

The second limitation is regarding the Collaboration Process Model used in this study. The simplified model was enough to help to define and identify the metrics but as survey results analysis showed it could be interesting to develop the model to a more detailed level to identify new specific metric and, ultimately, allow more precise comparison of tools and practices.

Finally this research didn't consider the different actors of the team but rather the team as an entity. As it was reported by experts in final interviews, the metrics may have different interpretation depending on which actors are involved. Therefore, further study should investigate the impact of this factor and eventually correct the metrics of their interpretation regarding the situation. Moreover the design phase was considered as a whole rather than having different phase itself. Nonetheless, it was identified by experts that the phase (early design, detailed design, others) should have an impact on the metric and their meaning.

The further studies, as confirmed by experts' interviews, would be to collect data from an appropriate number of projects to discover some common findings such as the characteristic curve-relation of each metrics. It would then enable to investigate the influence of different factors such as actors involved, communication process, communication tools, organizational structures, BIM tools and others and ultimately to identify the most performing practices. Iterations to improve the collaboration process model and the metrics based on analysis of collaboration practice from the data should be performed to improve the accuracy of the results.

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Appendix A – Pre-Selected Metrics

Category	Metric	Comment
Objects and Systems	Number of objects in the model	
	Number of objects created	
	Number of objects removed	
	Number of absolute objects number changes	
	Average number of generic objects per assembly	
	Number of modeled disciplinary systems	
	Number of objects per sq.f. of the buildings	
LoD	LoD in the 3D/4D model	
	Model LOD per number of coordination meeting	
Data	Number of break-down levels in the data structure	
	Number of data entries	
	Number of data changes	
Warnings and Clashes	Number of clashes detected	
	Number of clashes detected per object	
	Number of clashes found per costs scope of work	
	Number of warnings	
	Criticality of warnings	
	Number of hazards identified using 3D model	
	Commitment reliability	# clashes resolved on time / planned to be resolved.
Inconsistencies	Consistency of 3D model and 2D references	# of errors in reference to 2D deliverable/number of objects.
	Drawing coordination consistency	# of inconsistencies.
	Models' analytical reporting quality	# of objects needing to be modified or added before reporting / # of objects.
	Internal consistency of	% of inconsistent variables.

	design assumptions Discrepancies of each discipline's models	# of discrepancies/#of objects.
Change Orders	Change order rate Number of change orders Number of baseline revisions Number of scope changes approved Number of scope changes pending	
Response Latency and Processing Time	Average change order processing time RFI processing time Average response latency Average speed of information transmission through a team	
Request For Information	Number of RFIs RFI quantities in 2D vs 3D Percentage of on-time RFI to date	
Resubmittals	Number of resubmittals Percentage of submittals approved	
Design Iterations	Number of design iterations Number of iterations of BIM Number of local iterations Number of object modification Number of design alternatives modeled	
Time Spent	Percentage of time working on BIM Time to creating BIM Time to managing BIM Time spent communicating Time spent communicating per person	
Individuals	Number of persons engaged Number of individuals building BIM Number of individuals using BIM	

	Number of individuals reviewing BIM	
Costs	Cost of creating BIM Cost of managing BIM	
Information Transfers	Number of value-adding information transfer between designers Number of face to face communications Number of virtual communications Number of planned interactions Number of unplanned interactions Number of time the model gets accessed Number of BIM enabled project-wide meeting	
Information Contents	Number of statements about design trends Number of expressions of confusion Number of files upload per person Average amount of information in each transmission	

Appendix B – Survey Results

Metric	Question 1						Question 2					
	Convergence		Agreement		Variation		Convergence		Agreement		Variation	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Number of objects in the model	2.25	2.00	0.10	-1.00	0.62	0.70	1.50	1.50	0.00	0.00	0.62	0.62
Number of objects created	1.75	1.50	0.13	0.00	0.58	0.62	1.75	1.50	-0.17	0.00	0.60	0.60
Number of objects removed	1.25	1.00	0.38	0.50	0.38	0.40	0.75	1.25	0.63	0.38	0.35	0.37
Number of absolute objects number changes	1.00	1.50	0.67	0.40	0.42	0.50	1.50	1.50	0.40	0.40	0.48	0.48
Average number of generic objects per assembly	1.75	1.00	-0.17	0.33	0.65	0.62	1.00	1.75	0.33	0.13	0.53	0.55
Number of modeled disciplinary systems	1.50	1.25	0.50	0.58	0.49	0.49	1.50	1.25	0.40	0.58	0.48	0.47
Number of objects per sq.f. of the buildings	1.25	1.00	0.38	0.50	0.53	0.43	1.25	0.50	-0.25	0.50	0.54	0.47
LoD in the 3D/4D model	1.25	1.00	0.50	0.60	0.38	0.38	0.25	0.75	0.90	0.70	0.31	0.36
Model LOD per number of coordination meeting	1.50	1.00	0.00	0.33	0.60	0.50	1.50	1.25	0.00	0.17	0.62	0.63
Number of break-down levels in the data structure	1.25	1.00	0.50	0.60	0.38	0.32	0.50	0.50	0.83	0.83	0.30	0.31
Number of data entries	0.00	0.25	1.00	0.92	0.15	0.17	0.50	0.75	0.83	0.75	0.14	0.31
Number of data changes	1.50	1.25	0.40	0.50	0.43	0.35	0.50	0.50	0.80	0.80	0.22	0.22
Number of clashes detected	0.75	0.50	0.70	0.80	0.17	0.14	0.75	0.50	0.75	0.83	0.18	0.14
Number of clashes detected per object	0.50	0.00	0.83	1.00	0.18	0.15	0.50	0.75	0.83	0.75	0.18	0.31
Number of clashes found per costs scope of work	1.25	1.00	0.50	0.60	0.43	0.45	1.25	1.00	0.38	0.33	0.45	0.50
Number of warnings	0.25	0.50	0.90	0.80	0.36	0.38	0.50	0.75	0.83	0.70	0.37	0.41
Criticality of warnings	1.00	0.75	0.60	0.63	0.40	0.46	1.00	1.25	0.60	0.38	0.46	0.55
Number of hazards identified using 3D model	1.25	1.50	0.38	0.25	0.40	0.53	1.25	1.25	-0.25	0.38	0.52	0.40
Commitment reliability	0.50	0.25	0.80	0.90	0.22	0.20	0.75	1.25	0.50	0.38	0.32	0.41
Consistency of 3D model and 2D references	1.00	0.75	0.67	0.70	0.28	0.20	0.75	0.50	0.75	0.83	0.25	0.14
Drawing	0.25	0.25	0.92	0.92	0.11	0.12	0.50	0.25	0.83	0.92	0.14	0.12

coordination consistency												
Models' analytical reporting quality	1.00	1.00	0.67	0.60	0.23	0.35	0.75	1.00	0.70	0.60	0.21	0.24
Internal consistency of design assumptions	0.50	0.50	0.83	0.83	0.14	0.38	0.75	0.75	0.70	0.70	0.34	0.28
Discrepancies of each discipline's models	0.25	0.25	0.92	0.92	0.12	0.11	0.50	0.75	0.83	0.75	0.30	0.25
Change order rate	0.00	0.00	1.00	1.00	0.10	0.10	0.75	0.50	0.70	0.83	0.33	0.23
Number of change orders	0.00	0.50	1.00	0.83	0.10	0.10	0.75	0.50	0.70	0.80	0.26	0.16
Number of baseline revisions	0.00	0.50	1.00	0.83	0.13	0.21	1.25	1.25	0.50	0.58	0.35	0.30
Number of scope changes approved	0.50	0.25	0.83	0.92	0.13	0.36	1.00	0.75	0.60	0.75	0.28	0.38
Number of scope changes pending	0.25	0.75	0.90	0.70	0.18	0.23	0.75	0.75	0.63	0.70	0.26	0.24
Average change order processing time	0.50	0.50	0.83	0.83	0.08	0.12	0.75	0.50	0.75	0.83	0.27	0.24
RFI processing time	0.25	0.25	0.92	0.92	0.11	0.17	1.25	0.50	0.58	0.80	0.38	0.18
Average response latency	0.25	0.00	0.92	1.00	0.14	0.10	0.75	0.50	0.70	0.83	0.23	0.23
Average speed of information transmission through a team	0.50	0.50	0.80	0.83	0.18	0.10	0.75	0.50	0.70	0.83	0.26	0.13
Number of RFIs	0.50	0.00	0.83	1.00	0.28	0.35	1.00	0.75	0.60	0.70	0.46	0.39
RFI quantities in 2D vs 3D	0.75	0.25	0.70	0.90	0.31	0.37	0.75	0.75	0.70	0.70	0.37	0.33
Percentage of on-time RFI to date	0.50	0.75	0.83	0.70	0.23	0.17	1.25	1.25	0.17	0.50	0.43	0.37
Number of resubmittals	1.25	1.25	0.50	0.38	0.40	0.48	1.00	0.75	0.33	0.63	0.47	0.35
Percentage of submittals approved	1.25	0.75	0.38	0.70	0.38	0.31	1.00	1.25	0.50	0.38	0.44	0.42
Number of design iterations	0.75	0.75	0.75	0.75	0.24	0.19	1.00	0.75	0.60	0.75	0.24	0.18
Number of iterations of BIM	1.00	0.75	0.60	0.75	0.28	0.26	0.75	0.75	0.75	0.75	0.21	0.21
Number of local iterations	1.00	0.75	0.60	0.70	0.38	0.30	0.75	0.50	0.70	0.80	0.34	0.22
Number of object modification	0.75	0.50	0.70	0.80	0.17	0.18	0.75	0.75	0.70	0.63	0.24	0.20
Number of design alternatives modeled	0.50	0.50	0.80	0.80	0.21	0.14	0.75	0.50	0.75	0.80	0.21	0.14
Percentage of time working on BIM	1.25	0.75	0.50	0.70	0.35	0.21	0.50	0.25	0.80	0.92	0.28	0.12
Time to creating BIM	1.00	0.75	0.60	0.70	0.25	0.30	0.50	0.00	0.80	1.00	0.28	0.12
Time to	0.25	0.50	0.90	0.80	0.20	0.16	0.50	0.50	0.80	0.83	0.31	0.13

managing BIM												
Time spent communicating	0.25	0.00	0.92	1.00	0.23	0.10	1.50	0.75	0.25	0.70	0.47	0.31
Time spent communicating per person	0.50	0.50	0.83	0.83	0.18	0.23	1.25	1.00	0.38	0.60	0.44	0.38
Number of persons engaged	0.75	0.50	0.70	0.80	0.30	0.28	0.75	0.50	0.70	0.80	0.33	0.24
Number of individuals building BIM	0.75	0.50	0.70	0.80	0.26	0.22	0.25	0.25	0.92	0.92	0.17	0.36
Number of individuals using BIM	1.00	0.25	0.60	0.92	0.34	0.12	0.25	0.25	0.92	0.92	0.23	0.21
Number of individuals reviewing BIM	1.00	0.50	0.60	0.80	0.39	0.28	0.50	0.50	0.83	0.83	0.23	0.38
Cost of creating BIM	0.75	0.75	0.70	0.70	0.32	0.37	1.50	1.00	0.25	0.50	0.42	0.39
Cost of managing BIM	1.00	0.75	0.60	0.70	0.34	0.29	1.50	1.25	0.25	0.38	0.42	0.37
Number of value-adding information transfer between designers	0.50	0.75	0.83	0.75	0.14	0.25	0.00	0.25	1.00	0.92	0.22	0.23
Number of face to face communications	0.25	0.75	0.90	0.70	0.13	0.30	0.25	0.25	0.90	0.90	0.28	0.10
Number of virtual communications	0.75	0.75	0.70	0.75	0.20	0.21	0.75	0.75	0.75	0.75	0.19	0.21
Number of planned interactions	0.50	0.75	0.80	0.75	0.21	0.22	1.00	0.75	0.60	0.70	0.28	0.26
Number of unplanned interactions	0.50	1.00	0.80	0.60	0.16	0.23	0.50	1.00	0.80	0.60	0.29	0.32
Number of time the model gets accessed	0.50	0.50	0.83	0.83	0.13	0.31	0.25	0.25	0.92	0.92	0.11	0.17
Number of BIM enabled project-wide meeting	0.25	0.50	0.92	0.83	0.11	0.08	0.50	0.50	0.86	0.83	0.12	0.12
Number of statements about design trends	0.75	0.50	0.75	0.80	0.32	0.28	0.00	0.50	1.00	0.80	0.27	0.10
Number of expressions of confusion	0.75	0.50	0.75	0.83	0.15	0.18	0.75	0.50	0.70	0.83	0.17	0.13
Number of files upload per person	0.75	0.75	0.70	0.63	0.26	0.22	1.00	0.75	0.50	0.63	0.43	0.29
Average amount of information in each transmission	0.75	0.50	0.70	0.80	0.34	0.26	0.75	0.50	0.63	0.75	0.32	0.34

	Appropriateness	**Suitability**	**Criticality**	**ACVR**

	Mean	Rank	Mean	Rank	Mean	Rank	Value	Rank
Number of objects in the model	3.29	62	3.14	64	12.86	62	-0.71	52
Number of objects created	3.14	63	3.43	60	12.86	62	-0.71	52
Number of objects removed	3.71	57	4.43	45	17.29	56	-0.71	52
Number of absolute objects number changes	4.00	56	4.29	51	19.43	53	-0.43	44
Average number of generic objects per assembly	2.86	65	4.14	54	12.43	64	-0.71	52
Number of modeled disciplinary systems	4.71	42	4.57	42	25.71	36	0.14	18
Number of objects per sq.f. of the buildings	3.00	64	2.43	65	8.14	65	-1.00	64
LoD in the 3D/4D model	4.57	45	4.71	37	23.71	41	-0.43	44
Model LOD per number of coordination meeting	3.43	61	3.43	60	14.00	61	-0.71	52
Number of break-down levels in the data structure	4.71	42	5.57	11	27.86	26	0.43	5
Number of data entries	6.00	4	5.00	28	30.00	18	0.43	5
Number of data changes	4.57	45	4.86	32	23.14	44	-0.14	28
Number of clashes detected	5.29	25	5.43	13	29.00	21	0.43	5
Number of clashes detected per object	5.86	9	5.00	28	29.57	19	0.43	5
Number of clashes found per costs scope of work	4.43	50	3.43	60	16.57	57	-0.71	52
Number of warnings	4.57	45	4.43	45	22.71	46	-0.14	28
Criticality of warnings	3.71	57	3.43	60	15.43	60	-0.71	52
Number of hazards identified using 3D model	3.57	60	4.14	54	15.86	59	-0.71	52
Commitment reliability	4.71	42	3.86	58	18.14	54	-0.71	52
Consistency of 3D model and 2D references	5.57	16	6.00	2	34.00	6	0.14	18
Drawing coordination consistency	5.86	9	5.86	4	34.57	5	0.71	2
Models' analytical reporting quality	4.86	37	5.14	24	26.57	32	-0.14	28
Internal consistency of design assumptions	5.14	30	4.86	32	26.57	32	-0.43	44
Discrepancies of each discipline's models	6.14	3	5.57	11	34.71	3	0.43	5
Change order rate	6.00	4	5.43	13	32.86	10	0.43	5
Number of change orders	5.57	16	5.00	28	28.00	24	-0.14	28
Number of baseline revisions	5.29	25	4.86	32	26.86	31	0.14	18
Number of scope changes approved	5.14	30	4.86	32	27.71	27	0.14	18
Number of scope changes pending	5.00	32	4.71	37	24.43	40	-0.43	44
Average change order processing time	6.29	2	5.71	7	36.00	2	0.43	5
RFI processing time	6.00	4	5.43	13	33.14	9	0.71	2
Average response latency	6.00	4	5.43	13	32.86	10	0.43	5
Average speed of information transmission through a team	5.57	16	5.71	7	32.00	13	0.43	5
Number of RFIs	4.57	45	4.43	45	22.43	47	-0.43	44
RFI quantities in 2D vs 3D	4.43	50	4.57	42	21.29	48	-0.71	52
Percentage of on-time RFI to date	5.71	13	4.29	51	23.71	41	-0.43	44

Number of resubmittals	3.71	57	3.86	58	16.14	58	-0.71	52
Percentage of submittals approved	4.57	45	4.29	51	21.14	50	-0.43	44
Number of design iterations	5.71	13	5.29	21	30.71	15	0.14	18
Number of iterations of BIM	5.29	25	5.43	13	29.14	20	-0.14	28
Number of local iterations	4.86	37	4.86	32	24.86	38	-0.14	28
Number of object modification	5.43	21	4.71	37	25.86	34	-0.43	44
Number of design alternatives modeled	5.29	25	5.29	21	28.29	23	0.14	18
Percentage of time working on BIM	5.29	25	5.86	4	31.43	14	0.14	18
Time to creating BIM	4.86	37	5.00	28	24.86	38	-0.14	28
Time to managing BIM	5.00	32	5.71	7	28.86	22	-0.14	28
Time spent communicating	6.00	4	4.57	42	27.57	28	-0.14	28
Time spent communicating per person	5.43	21	4.14	54	23.43	43	-0.14	28
Number of persons engaged	5.00	32	5.29	21	25.86	34	-0.14	28
Number of individuals building BIM	4.86	37	5.14	24	25.57	37	0.14	18
Number of individuals using BIM	5.86	9	5.43	13	32.29	12	0.43	5
Number of individuals reviewing BIM	5.00	32	5.14	24	28.00	24	0.14	18
Cost of creating BIM	4.43	50	4.43	45	21.29	48	-0.14	28
Cost of managing BIM	4.14	54	4.43	45	19.86	52	-0.14	28
Number of value-adding information transfer between designers	5.57	16	5.86	4	33.29	8	0.43	5
Number of face to face communications	4.86	37	4.71	37	23.00	45	-0.14	28
Number of virtual communications	5.43	21	5.43	13	30.57	16	0.14	18
Number of planned interactions	5.71	13	5.14	24	30.57	16	0.43	5
Number of unplanned interactions	5.43	21	4.71	37	27.00	29	-0.14	28
Number of time the model gets accessed	5.57	16	6.00	2	34.71	3	0.71	2
Number of BIM enabled project-wide meeting	6.43	1	6.29	1	40.71	1	1.00	1
Number of statements about design trends	5.00	32	5.43	13	27.00	29	-0.14	28
Number of expressions of confusion	5.86	9	5.71	7	33.71	7	0.43	5
Number of files upload per person	4.14	54	4.00	57	17.43	55	-1.00	64
Average amount of information in each transmission	4.29	53	4.43	45	20.14	51	-0.71	52