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INVESTIGATING MODEL EVOLUTION IN A COLLABORATIVE BIM ENVIRONMENT

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Abstract: As the adoption and implementation of building information modeling (BIM) continues to gain momentum, the benefits and challenges of its implementation and use are becoming better defined. However, there still lacks an understanding into the reconfiguration of practice that is being induced by BIM within multi-disciplinary project teams. Part of this reconfiguration of practice involves the development of the model through the generation, authoring and exchange of project information. This paper presents the finding of a research project that investigated the evolution of a BIM developed by a vertically integrated project team on a large institutional project for design and construction purposes. The objective of the research project was to develop measures to investigate the evolution of a BIM in a collaborative and multi-disciplinary project setting. The research team analyzed the bi-weekly iterations of the models produced by the design team following a rigorous protocol. Timesheets were obtained for all project team members involved in the modeling process. The measures developed adopt both the product and the process perspective of BIM. These measures were tested to verify how they correlated to one another and to the overall time spent in the project and in BIM. Four categories of measure are developed: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. These measures can serve as a benchmark to evaluate the efficiency of the modeling and ultimately the project delivery process.

1 INTRODUCTION

The transition to building information modeling (BIM) based practice in the Architecture, Engineering and Construction (AEC) industry promises considerable benefits over traditional practice mainly due to the possibility for project teams to co-develop, coordinate and optimize the digital prototype of a product (building, infrastructure, etc.) prior to its execution. This prototype is developed as a parametric model, acting as a database containing a product's information available for reuse during its entire lifecycle (Eastman et al., 2011). These benefits are accrued through better information authoring, exchange, management and retrieval (Crotty, 2011); in theory BIM is allowing project teams to mitigate information chaos in the project lifecycle (Dubler et al., 2010). Considering that project teams can be considered information processing systems (Winch, 2010), this push to eliminate information chaos within the project team is central to one of the core tenants of BIM which is to improve the efficiency and performance of the AEC industry (Eastman et al., 2011). On the other hand, the transition to BIM constitutes a departure from traditional practice (Dossick and Neff, 2011). As such, organizations are currently caught in a period of disruption in the AEC industry: the promise of BIM is alluring to many and in this regard, they are moving forward with its implementation. However, they are being confronted to deeply entrenched practices, hence the notion of paradigm shift and the need to reconfigure these practices to leverage the benefits of BIM (Taylor and Bernstein, 2009). While theoretical developments in the area of BIM implementation are taking root, there is still a need to define and assess how this shift is affecting practice and more precisely how it is impacting the generation, authoring, exchange and management of project information across a project's lifecycle. From this perspective, this paper aims to increase our understanding of how a BIM evolves throughout a project and the factors that mediate its progression by developing measures to investigate its evolution in a collaborative and multi-disciplinary project setting. This paper specifically aims to answer the following questions: (1) what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? (2) How do these measures correlate between themselves, across time and across disciplines? And (3) what do these measures tell us of how a BIM is evolving throughout the project? The case study of a new institutional building procured under a design-build delivery mode is used to develop these measures and answer these questions. Four categories of measure were developed: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. Other measures that have been developed are discussed in the paper, however they were not operationalized. These measures are: measures of project complexity, measures of information quality and measures of information flow. The paper concludes with a discussion about the implications of these measures as well as opportunities for future work.

2 BACKGROUND

The transition to BIM is not without its set of challenges (eg. Eastman et al. 2011), chiefly amongst them, interoperability, or the ability of heterogeneous information systems to communicate (IEEE, 1990) is consistently ranked as a top barrier to BIM. Amongst the many dimensions of interoperability identified (Poirier et al., 2014), technological interoperability remains one of the most important issues which hinders the flow of information in current BIM-based project environments. While strategies to overcome these issues have been developed, namely the OpenBIM standards developed by buildingSMART International, they are still in development. Furthermore, organizational, procedural and contextual barriers, that have been documented in the past, prior to the emergence of BIM, (e.g.Egan, 1998) are still having as important, if not a bigger, impact on the flow of information within the project team than the newly introduced technological barriers. In light of these challenges, different approaches to formalize information handoffs in a BIM-based collaborative environment have been developed, namely the information delivery manual (IDM) part of the OpenBIM standard from buildingSMART International (ISO 29481-1, 2010), the model elements table developed by the American Institute of Architects (AIA) in 2008 (AIA, 2008) , the Level of Development (LOD) Specifications developed by the BIMForum released in 2013 (BIM Forum, 2013), as well as the COBie data exchange format developed by the USACE in 2007 and in particular the Data Drops developed in conjunction with the BIM task group in the UK (East, 2007). While these approaches allow to either map out or align model based information authoring and exchanges expectations, they represent set points in time and are often aligned to the tradition project phases, further contradicting the required change in practice to move towards seamless information flow through BIM. Furthermore, these approaches do not allow to assess the dynamic nature of information throughout a project.

Sparse work has looked into the assessment of model evolution in the AEC industry. As such there are little metrics to perform a comprehensive evaluation. However, some work has been performed to investigate specific elements which touch on model-based information evolution. Leite et al. (2011) investigate the effort that it takes to develop a model from a LOD 400 to LOD 500. The main objective is to evaluate the modeling effort in relation to the level of detail. They then evaluate the impact of LoD in supporting MEP design coordination. The study shows that additional modeling effort can lead to more comprehensive analyses and better decision support during design and construction. Sacks et al. (2005) provide a set of benchmarks to evaluate the BIM implementation process in terms of productivity gains between a traditional 2D CAD workflow and a 3D modeling workflow. They go on to find that the transition to BIM has improved productivity between 15% and 41% for design and detailing in structural engineering practice (Sacks and Barak, 2008). East and Bogen (2012) propose an experimental platform and a methodology to consistently evaluate building models. The tools proposed are experimental and mainly for research purposes. Du et al. (2014) propose a cloud-based BIM performance benchmarking application, called BIM Cloud Score, to allow an overall view of BIM utilization in the AEC industry and facilitate performance improvement for individual companies. The authors developed a series of 6 indicators and 21 measures for the assessment of both the process and the product (the model). The BIM Cloud Score is still a hypothetical tool and has yet to be commercialized. Furthermore, some of the metrics, information quality as an indicator of performance for instance, are summarily discussed and lack robustness. To that effect, Berard (2012) develops 8 specific metrics and describes a scale of observable phenomenon (akin to a maturity model) to evaluate information quality from the contractor's perspectives. He operationalizes these metrics to validate their applicability and usefulness in the AEC industry. While useful, the contractor perspective is narrow and the author doesn't differentiate between quality of information processes and quality of the product information itself. Dubler et al. (2010) look into the question of process information and study information exchanges through BIM from a lean perspective. They develop the 7 types of waste identified in the Lean approach and map that to types of waste related to information exchanges through BIM. Manzione et al. (2011) develop a BIM Integrated Management Model (BIMM) comprised of four stages, called *loops*, and a total of 11 steps. In the *control loop* they operationalize the 6 indices (or measures) of information flow developed in Tribelsky and Sacks (2010) and based on lean concepts. These indices allow measurement of information flow in the process of detailed design where construction documents are prepared. The indices develop in Tribelsky and Sacks (2010) identify information flow bottlenecks, large batch sizes and accumulation of work with the objective of finding faults or bottlenecks in the project development process. They also developed an index for measuring rework which was later validated in Tribelsky and Sacks (2011). In this subsequent paper, the authors find that an unpredictable information flow results in unpredictable project outcomes. This body of work pertaining to evaluating information flow is highly relevant and speaks to the shift in practice from this perspective. In parallel, the BIMM offers a framework to structure how this information should be managed in a project delivery setting. However, certain areas of evaluation are lacking such as information quality, design evolution and productivity. Other domains have looked into assessing the evolution of design and production. Namely, the field of software engineering has developed many measures to evaluate the development (e.g.Ampatzoglou and Chatzigeorgiou, 2007) and quality of software design (e.g.Yacoub et al., 1999). In order to close the gap identified in terms of comprehensive evaluation of design development and evolution in the AECO industry in light of the reconfiguration of practice prompted by BIM, the developments in these fields could be leveraged and applied to the AEC industry. The table below presents various metrics to evaluate different aspects of design and product evolution (table 1)

Table 1: Measures to evaluate design and product evolution from various domains

Author	Du et al. 2014	Berard 2012	Dubler et al. 2010	Tribelsky and Sacks 2010	Ampatzoglou Chatzigeorgiou 2006	Yacoub et al. 1999
Domain	AEC	AEC	AEC	AEC	Software	Software
Purpose	Product and process performance	Information quality	Information exchange waste	Information flow	Software size & complexity	Software quality
Metrics	Productivity – speed of development Effectiveness Quality Accuracy Usefulness Economy	Relevance Consistency Correctness Precision Availability Distribution Flexibility Amount of information	Overproduction Inventory Extra Processing Motion Defects Waiting Transportation	Action rate package size work in progress rework batch size development velocity bottleneck	Size (Lines of code, number of classes) Complexity Coupling Cohesion	Complexity Coupling Dynamic coupling

3 RESEARCH METHODOLOGY

This research project is part of a larger more comprehensive research project aimed at studying the impact of BIM on project delivery in the AEC industry. The aim of this particular scope of the research project was to investigate the evolution of a BIM in a collaborative, multi-disciplinary project environment by answering the following questions: (1) what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? (2) how do these measures correlate between themselves, across time and across disciplines? And (3) what do these measures tell us of how a BIM is evolving throughout a project? In light of this, the objective of this scope of the research project was to develop and test measures to evaluate the development of information through a BIM. To fulfill these objects, a mixed-method case study methodology was employed. The case studied is that of the new construction of a major institutional building in Edmonton, Alberta, Canada. The $260 million, 39,000 m^2, project was procured under a design-build contract with the government of Alberta. The project team was made up of 29 different stakeholder organizations. For the scope of research described in this paper, the research team performed data collection over an 18 month period, which corresponded to the construction documentation phase of the project. More precisely, the research team collected the bi-weekly iterations of the models produced by the design team over this 18 month period and analyzed them following a rigorous protocol. 41 iterations of the model were analyzed for the four main disciplines: architecture, structural, mechanical and electrical, for a total of 164 models. The models were analyzed in their native format (Autodesk Revit 2012 & 2013) and in a model checking and coordination software (Autodesk Navisworks Manage 2014). The models were all purged to remove all unused elements prior to analysis to ensure consistency. Furthermore, Industry Foundation Class (IFC) files were produced for every model and analyzed using the text file, the NIST IFC Analyser (Lipman, 2011) and Solibri Model Checker v.9.5. This was done to expand the scope of analysis to include measures such as Lines of Code in the IFC schema, number of entities, model components and model revisions. Table 3 presents these measures. Timesheets were obtained for all project team members involved in the design and model development process. The total hours spent on the project and the number of hours spent by BIM personnel (individuals who were working directly in the model) were compiled. The measures were analyzed in three ways: the correlation between the measures, the correlation of the measures between the disciplines and the evolution of the measure across time were calculated for all disciplines and between disciplines. The 'R' language and environment for statistical computing was used (R, 2008). Spearman's rank correlation coefficient (ρ) was used to evaluate the correlation between variables due to its sensitivity to monotonic relationships over linear relationships. A cluster analysis was also performed in R to evaluate the appropriateness of the measures developed. The analysis were run for both absolute values (cumulative, ρ_{abs}) and relative values (variance per time period, ρ_{var}) for each measure.

Table 3: Data collection points for model analysis across all disciplines

Native model	IFC file	Timesheets
File size (purged)	File size	Total hours per discipline
Scheduled Objects	LOC in the schema	BIM hours per discipline
Quantities – all	Entities	
Clashes	Components	
Sheets created	Model revisions	
Views created		
Annotations (Legends, etc.)		

3.1 Project setting

The context of the case studied was characterized by the following elements: it was a publicly funded project procured under a design-build agreement with the provincial government. The design team was from a vertically integrated firm offering architectural and engineering services. As such, the core design team was working on the same network in real-time. Bi-weekly updates of the models were published to a cloud-based project management software to be distributed to the general contractor and sub-trades. Key sub trades were contracted in a design assist role and provided a gross maximum price upon completion of design development. The contracts with the sub-trades and with the client were based on 2D drawings and specifications. As such, the model represented the core database containing project information, however a lot of effort was put into preparing and distributing 2D documents, which themselves contained annotations and specifications that were not found in the model. Therefore, it cannot be said that the model contained all relevant project information. A BIM project execution plan (PxP) was prepared to outline the scope and uses of the model in the project. On key element that was introduced in the PXP was the "Statement of Collaboration Intent" which outlined the intentions of each project stakeholder with regards to BIM use in the project. This is where the level of development was detailed for all disciplines and for all model elements. For example, the statement of collaboration intent for the architectural discipline was the following: "*Most elements will only have as much data as we need to produce a 2D set of drawings"*. This particular statement was made because the contractual documents and all deliverables for the project were to be 2D documents. Any further modeling that was required for coordination and fabrication purposes would have to be performed by the trades. The active participants in the modeling process on the project were the following: architecture, interior design, structural engineer, mechanical engineer, electrical engineer, general contractor, structural steel contractor, mechanical contractor, electrical contractor. Furthermore, the project context was particular in that, even if this was a design-build project, the client still had considerable involvement during the design phase. The project team had to release progress documents at set milestones, both internally for costing updates and externally for project review by the client. Therefore, two parallel work streams were developed whereby part of the design and documentation effort was put on developing the model and part of that effort was put on producing the 2D documents. Despite this particular context, it is still possible to say that this project was a collaborative BIM-enabled, multi-disciplinary project, with early involvement of key trades and general contractor. In this regard, the evolution of the BIM was intimately tied to the evolution of the project. In the evaluation of the various models, it is assumed that the modeling process is consistent throughout the project and across the project team.

4 FINDINGS

4.1 Measures developed

All disciplinary models were thoroughly analyzed to answer the first question: what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? The thorough investigation of the models allowed us to extract the 12 variables presented in the first two columns of table 3 and view their evolution across time for all four disciplines. Addressing the second question (how do these measures correlate between themselves, across time and across disciplines?) facilitated a categorization of the measures as follows: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. Lastly, the third question (what do these measures tell us of how a BIM is evolving throughout a project?) was addressed for each category to evaluate how the measures identified vary in relation to time spent on BIM by the various disciplines in the project team. Figure 1 illustrates the relationships between the measures of model evolution. Figure 2 illustrates the percentage variance of the four measures at a given period for all disciplines. This percentage variance could be compared to the project average for each measure, compared against a given target, or in the case of a retrospective study such as this one, against the final model which serves as a benchmark.

4.1.1 Measures of information quantity: File size and lines of code in the schema

The measure of information size is a reflection of the overall information contained within the model in terms of bytes of encoded data or information. This measure is represented by file size (both from the purged native file and the IFC file) and the number of lines of code in the IFC schema (LOC) (from the IFC file). The main issue with file size as a measure is in the way the information is encoded by the software platform or how the model is created, with issues associated to the modeling process and elements included in the model. Native file size includes all geometry in the model, properties, relations, annotations, views, sheets, images or renders and other representations that would support the project

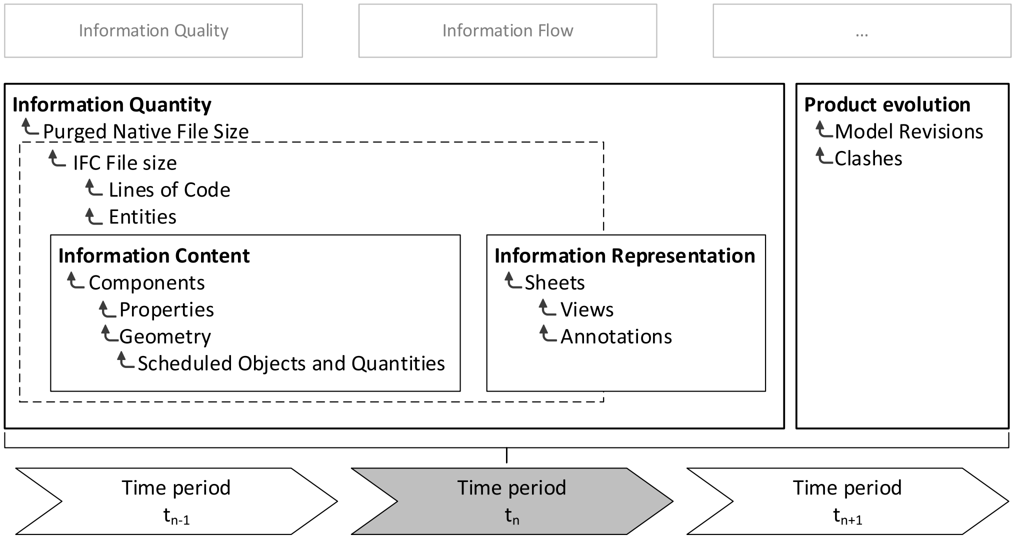
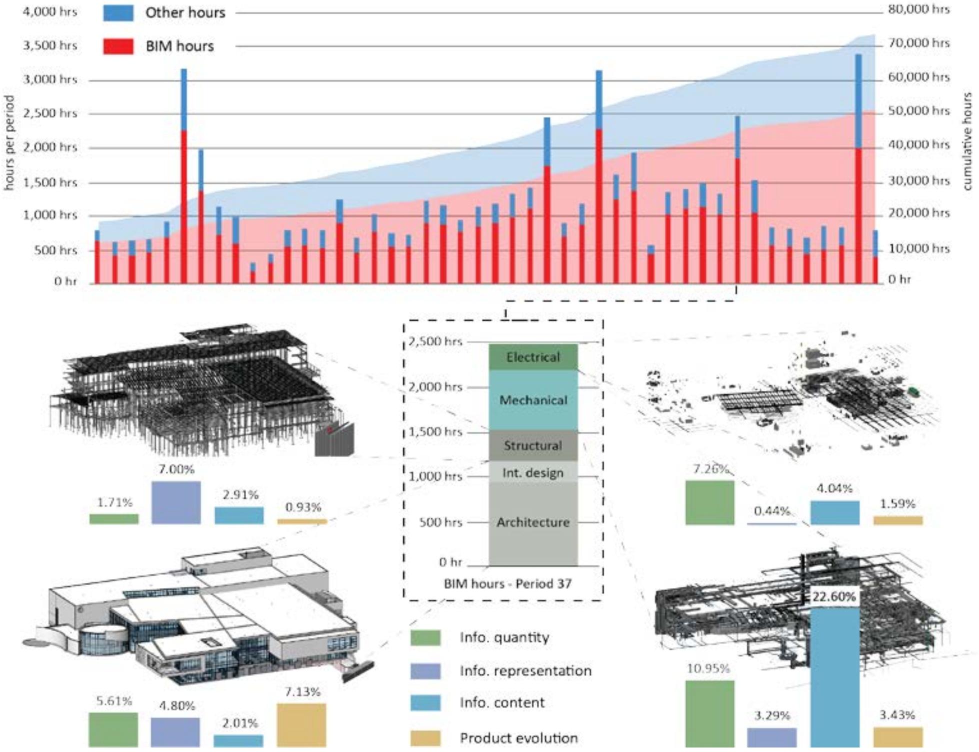


Figure 1: Relationship between measures of model evolution



development process, whereas the IFC files only contain the information that was processed at export, which in itself introduces variability due to the potential loss of information during export (Koch and Firmenich, 2011). It must be noted that a version upgrade was performed (from 2012 to 2013 version) for the native software used in the project, which could impact how the IFC files were exported. Regardless, IFC file sizes and LOC are very strongly positively correlated across all disciplines (min ρ_{var} = 0.898 for architectural). There is a mid-positive correlation between purged native file size and IFC file size for mechanical (ρ_{var} = 0.506), while it is considerably lower for electrical (ρ_{var} = 0.265) and architectural (ρ_{var} = 0.163), which could be caused by information that is not directly included in the model, such as renders, or level of detail of model elements. A quasi-null, although negative, correlation was found for structural

(ρ_{var} = -0.042), perhaps due to how individual structural members are encoded in the native file as opposed to the IFC file. In the analysis of the correlation of measures of information quantity between disciplines, there is a low positive correlation between all disciplines for purged native model size meaning that file sizes are not particularly coupled across disciplines ($0.179 < \rho_{var} < 0.386$). There is a weaker correlation and more variability between IFC model sizes across disciplines ($-0.270 < \rho_{var} < 0.482$). A low to mid positive correlation was found between the time spent in BIM and the file size variation for all disciplines ($\rho_{var\ arch}$ = 0.309, $\rho_{var\ struc}$ = 0.405, $\rho_{var\ mech}$ = 0.702, $\rho_{var\ elec}$ = 0.670), which indicates a direct relationship between time spent in BIM and the purged native file size. The weaker correlations in architecture and structure could be in part due to the negative variations in size, for instance when certain elements in the model were rationalized. In investigating the evolution of measures of information quantity in relation to time spent in BIM over the course of the project, it was observed that the native file sizes for all disciplines progressed in a linear fashion whereas IFC files sizes jumped drastically at set points in time for both mechanical and structural.

4.1.2 Measures of information content: Entities, components, scheduled objects and quantities

The measure of information content relates to the geometry and properties of the elements in the model. While the number of entities in a model can be interpreted as a direct measure of the raw yet structured information contained in the IFC schema - there is a perfect correlation between LOC (consequently, IFC files size) and number of entities (ρ_{var} = 1.000) across all disciplines - the export to IFC process can introduce variability as mentioned. Therefore the measures of components and scheduled objects, which are attributable to model authoring and the project development process, would seem better suited for this measure. Indeed, individuals interact directly with these components in developing the model. The main difference between scheduled objects (extracted from the native file) and model components (extracted from the IFC file) are their practical use: scheduled objects are related to model uses whereas model components are related to model authoring. A mid to strong positive correlation was found between the number of entities and the number of components for all disciplines ($0.655 < \rho_{var} < 0.810$). There was also a mid to strong positive correlation between the number of scheduled objects and the number of components for all disciplines ($0.415 < \rho_{var} < 0.688$) In the evaluation of the correlation of measures of information content between disciplines, specifically components, a low to mid positive correlation was found between all disciplines ($0.103 < \rho_{var} < 0.696$). A low to mid positive correlation was found between the time spent in BIM and the variation of number of components for all disciplines ($\rho_{var\ arch}$ = 0.105, $\rho_{var\ struc}$ = 0.189, $\rho_{var\ mech}$ = 0.301, $\rho_{var\ elec}$ = 0.418). In investigating the evolution of measures of information content over the course of the project, it was observed that architectural (3.3% avg. increase) and structural (0.8% avg. increase) disciplines tended towards a slow progression of model components and scheduled objects whereas mechanical and electrical had ‘tipping points’, directly related to project milestones (in this case work packages) where a lot of content was created rapidly.

4.1.3 Measures of information representation: Views, sheets and annotations

The creation of views, sheets and annotation supports the design process and become the deliverables for the project. Views are embedded into sheets and annotated to create project documents. The presence of these elements are a characteristic of the parallel 2D – 3D modeling and documentation process. Whereas measures of information content tends to stabilize during the construction documentation workflows; the number of views and sheets continues to grow as the need for additional representations are required to translate and communicate project information to the various project team members. While the definition of what is represented on sheets is an industry standard (ie. plans, elevations, sections, details and schedules), views are highly contextual and not only discipline specific but subject to individual workflows, meaning that there is limited correlation between the number of views and sheets; each sheet will contain at least one view or schedule, but not all views and schedules will be included in a sheet. A low positive correlation was found between number of views and sheets across each disciplines ($0.181 < \rho_{var} < 0.277$); this measure is unrelated between disciplines. A low to mid positive correlation was found between the time spent in BIM and the variation of number of views for all disciplines ($\rho_{var\ arch}$ = 0.112, $\rho_{var\ struc}$ = 0.101, $\rho_{var\ mech}$ = 0.284, $\rho_{var\ elec}$ = 0.446). In the investigation the evolution of measures of information representation over the course of the project, the architectural discipline has the highest total number and the most rapid progression of views, however structural discipline has the highest views to sheet ratio at 12.82 views per sheet on average. Understanding the rate of information representation progression can allow to evaluate the time spent on the production of 2D drawings, a relatively redundant procedure given the emerging uses of BIM directly on site and in facilities maintenance.

4.1.4 Measures of product evolution: Clashes and Revisions

The overall variation of the above measures (quantity, content and representation) over time will be measures of information evolution. Product evolution and information evolution are differentiated in this case. As such, the number of clashes and revisions in the model can be interpreted as a measure of the refinement of the model as design progresses. The measure of clashes is extracted through clash detection software and is a standard process in current BIM based practice. Three classes of clashes have been developed: true-positives (identified as a clash and is a clash), false-positives (not identified as a clash but is a clash) and false-negatives (identified as a clash but is not a clash) (Leite et al. 2011). In addition, clashes were totaled for each discipline. The number of revisions is extracted by directly comparing model iterations in a model checking software. Three classes of revisions were extracted: elements added, elements removed and elements modified (elements that have one or more characteristic modified). Evaluating the correlation of measures of product evolution between disciplines, the number of revisions showed mid positive correlation ($0.393 < \rho_{var} < 0.641$), whereas the number of clashes show higher positive correlation ($0.608 < \rho_{var} < 0.915$). One element of note is that the design team did not start purposefully addressing clashes before the very end of construction documentation, therefore the measure of the evolution of clashes throughout the project is more or less a valid measure in this case. Furthermore, the models were released on a bi-weekly thus allowing the project team to complete any coordination cycle and thus the clashes that were found would be resolved in the upcoming cycle. Moreover, evaluating the correlation between the number of clashes and the number of revisions would seem a valid point of investigation, indeed this could indicated that clashes reduce as revisions increase, which would be a valid statement. The contrary however wouldn’t make sense. In evaluating this measure, the research team found a null to low correlation ($-0.214 < \rho_{var} < 0.227$), which confirms that the two measures are weakly related, if not unrelated. A null to mid correlation was found between the time spent in BIM and the variation of number of clashes ($\rho_{var\ arch} = 0.146$, $\rho_{var\ struc} = -0.073$, $\rho_{var\ mech} = 0.420$, $\rho_{var\ elec} = 0.494$) and the variation of the number of revisions ($\rho_{var\ arch} = -0.024$, $\rho_{var\ struc} = 0.230$, $\rho_{var\ mech} = 0.573$, $\rho_{var\ elec} = 0.370$). In the investigation the measures of product evolution over the course of the project, no clear trend was discernible for both number of revisions and number of clashes. It would be expected that both would tend towards 0 over time.

4.2 Additional measures: Measures of project complexity, information quality and flow

The measure of model complexity and of level of development are difficult to quantify. While specifications exist for level of development (eg. AIA, 2008), the exercise is carried out manually and remains somewhat subjective. In terms of complexity, some measures could be used such as use of generic model elements and place holders or number of objects per area (Du et al. 2014). Clevenger and Haymaker (2011) have developed some measures of complexity in the design process which could be further investigated in the context of model evolution. However, further work is required to develop measures of complexity that are relevant and directly computable as both measures of product and process in a BIM environment, namely in the investigation of complexity, coupling and cohesion in the IFC schema. Lastly, as discussed, measures of information quality and flow are core to the AEC industry. While the question of information flow has been tackled from various perspectives, the question of information quality is seemingly underrepresented in the AEC research domain. One could say that information flow is a subset of information quality as a measure of process efficiency and quality. The work performed by Dubler (2010) and Berard (2012) speak to these measures, however, they remain difficult to operationalize. For instances, measures of information accuracy and precision have to be validated in the field and compared to a suitable referent. Measures of information relevance are highly subjective and dependent on a stakeholder’s perspective. Trieblesky and Sack’s (2010, 2011) as well as Demian and Walters’ (2014) work tackled some of these issues with information flow, however, the authors acknowledge that the work performed was extremely onerous. Furthermore, while information exchanges can be more readily mapped and measure, information quality is highly subjective and dependant on the stakeholder's point of view. Information, its value and its quality in the model is a field of research that requires much more investigation.

5 DISCUSSION AND CONCLUSION

This paper presented the findings of a research project with the aim of investigating model evolution in a collaborative multi-disciplinary BIM-based project setting. Measures were developed to assess this evolution and allow a consistent empirical approach to information evolution in the project delivery process. The measures were tested for correlation between each other, across disciplines and their variation was evaluated across time. While most measures identified were correlated within their categories, further investigation is required to understand this implication across other project settings. Work is also necessary to understand proportionality in the evolution, for instance spending a lot of time on a particular 2D detail will not increase the weight of the model as adding or duplicating a specific component, say a piece of furniture, which takes a lot less time and contributes . Furthermore, in developing these measures and gaining access to data, the research team was faced with multiple challenges. A clear advantage was gained through BIM in this research project due to the possibility of querying project information in a structured manner. However, it would have been advantageous to have access to weekly iterations instead of bi-weekly iterations of the model. The exercise would have gained in precision. In addition, a main challenge was faced in developing a coherent measure of time spent in BIM versus time spent on the model. The research team did not have access to the file logs, nor did the time sheets completed by the employees contain relevant cost codes for various BIM activities. Time spent in BIM had to be extrapolated from the personnel that were identified as BIM users in the project. An additional challenge lay in exporting the IFC files in a consistent manner across different versions of the native software platform. IFC 2x3 was the standard format for export, and a special IFC export plug-in was used, however the mechanics behind the export were unknown to the research team and was seen to introduce a lot of variability between versions of the software platform. There is also some inherent loss in information in the transfer process (Koch and Firmenich, 2011) Moreover, while it was assumed the modeling process be consistent across the project team, each individual has their own way of working and interacting with the model, for instance creating 2D views to modify the model rather than working directly in 3D. This differences introduce variability in the investigation. In analysing the data, the research team was confronted with the choice between absolute values (ie. the compiled value or sum of values since the start of the project) and relative values (the variation between model iterations). Absolute values were used for correlation analysis in this paper whereas, the relative values were used in the time analysis. In the data extraction process, a rigorous protocol was required to replicate every step across the entire project. The research team is looking into automating this process for future work. It is also seeking to expand the scope of data extraction through the use of tools such as COBie data drops and the spreadsheets produced as a formal way to validate project progress. Further work is also required to replicate this evaluation across various project settings. However, in expanding this investigation to include different models, a considerable effort to normalize the data across the different project contexts will have to be carried out. For instance, the uses of BIM which impact the development of the model will have to be factored. The analysis of additional models would allow the regression analysis of multiple data sets to validate the evolution of the measures developed in this paper.

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