# Interactive Visual Analytics for BIM Compliance Assessment and Design Decision-Making

by

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## Abstract

The widespread adoption of Building Information Modelling (BIM) in the Architecture, Engineering, Construction and Owner (AECO) Industry has led to data-intensive projects. The growth of data in the digital environment may affect compliance with the Owner's BIM requirements and the overall project goal to utilize BIM for downstream purposes. Existing compliance assessment practices utilized by industry are very cost and time intensive, and ineffective at supporting design decision-making. Three specific challenges were observed in our research. First, the quality of information integrated in the BIM models may be inaccurate, thus impacting the integrity of BIM and posing a risk to the project. Second, the inundation of unstructured data generated in the BIM environment impacts the team's ability to manage information and extract useful insights to drive actions. Third, project stakeholders are often less involved than BIM experts in the BIM compliance process due to limited understanding of BIM platforms and drive their business-level decisions without understanding the status of design data.

The objective of this research is to address these three specific challenges using an action-research (AR) methodology. We present the outcomes of an action-research (AR) project undertaken with a global design consultant, Stantec, in the context of the design of a large healthcare facility. The objective of AR was to create a robust yet simple-to-use compliance assessment workflow. The key metrics for BIM compliance were identified and evaluated over the course of this study.

An automated data analytics and visualization workflow was developed to simplify the compliance assessment process of BIM-based projects. Visual programming was used to

automate the BIM data analytics to represent key compliance metrics and streamline complex workflows. The interactive visualization provides actionable information to project teams in a way that enables project experts to gain insights more effectively to inform decisions and to help manage compliance with Owner's BIM requirements. The workflow developed in this research was utilized by the design consultants on the case study project to achieve compliance with the Owner's BIM requirements, and the Regional BIM Lead at Stantec decided to use this workflow on all their BIM projects across the province.

## Lay Summary

The widespread adoption of Building Information Modelling (BIM) during design and construction has led to data-intensive projects. This data intensiveness has introduced various challenges in the delivery of BIM projects. These challenges greatly affect the compliance with the Owner's BIM requirements. Existing compliance assessment practices utilized by the industry are very cost and time intensive, and ineffective at supporting design decision-making. This study aims to reduce the complexity of compliance assessment by developing an automated analytics and visualization workflow, using an action-research methodology. This new workflow uses an interactive data visualization platform to provide actionable information to the teams to help manage compliance with Owner's BIM requirements and enable project experts to gain insights more effectively to inform decisions.

## Preface

This thesis is based on the Author's work with an engineering and design company, Stantec Consulting Ltd., under the direct supervision of Dr. Sheryl Staub-French. The Author is responsible for identifying and setting up the research theme of this work. The Author is also responsible for the data collection, analysis and research outcomes presented in this study. Unless cited, all the figures and tables presented in this thesis are developed by the Author.

The work presented in this thesis is intended to be submitted for future publications after slight modifications, under the guidance of Dr. Sheryl Staub-French.

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## List of Abbreviations

API: Application Programming Interface

AR: Action Research

BEP: BIM Project Execution Plan

BI: Business Intelligence

BIM: Building Information Modelling

BSR: BIM Standard Requirements

DGS: Data and Geometry Specifications

FMO: Facilities Maintenance and Operations

IQ: Information Quality

PM: Project Management

QC: Quality Control

VPL: Visual Programming Language

## Acknowledgements

I would like to express my sincere gratitude to my research supervisor Dr. Sheryl Staub-French for guiding and supporting me throughout this study. This work wouldn't have been possible without her support from the beginning of this research. The collaboration with the industry to conduct this research would not have been possible without her endless efforts and support.

Special mention goes to my industry supervisor and mentor – Mr. Aubrey Tucker and Mr. Ryan Wells who provided technical, financial and moral support during the data collection phase of this research. Their suggestions and guidance played a key role in making this research as relevant as possible to the industry professionals.

I would also like to thank Dr. Puyan A. Zadeh for helping me structure my research content during the initial stages. I offer my enduring gratitude to the faculty, staff and my colleagues at UBC, who have inspired me to continue my work in this field.

Finally, special thanks are owed to my parents and friends, whose have morally supported me throughout my years of education at UBC and stay in Canada.

*To my Family*

# Chapter 1: Introduction

## 1.1 Background and Problem Statement

The widespread adoption of Building Information Modelling (BIM) in the Architecture, Engineering, Construction and Owner (AECO) Industry has led to data-intensive projects. This intensiveness of data generated in digital environment has been observed to induce three specific complexities in the project delivery. First, the quality of information integrated in the BIM models may be inaccurate, thus impacting the integrity of BIM and posing a risk to the project. Second, the inundation of unstructured data generated in the BIM environment impacts the team's ability to manage information and extract useful insights to drive actions. Third, project stakeholders are often less involved than BIM experts in the BIM compliance process due to limited understanding of BIM platforms and drive their business-level decisions without understanding the status of design data. These specific issues significantly affect the compliance with the Owner's BIM requirements. Incompliance with the Owner's BIM requirements can directly affect the project scope, the Owner's building lifecycle management goals and the stakeholders involved can likely miss a crucial opportunity to make their services more valuable to the Owners.

Existing compliance assessment practices utilized by the industry are very cost and time intensive, and ineffective at supporting design decision-making, which was the motivation for this research. Although the quality of BIM and its impacts have been studied in previous literature, there has been limited research to evaluate BIM quality during project development and simultaneously propose actionable measures in real-time to the project stakeholders to inform design decisions. Considering the exhaustiveness of information involved, an innovative approach to this problem using data analytics and visualization has not been observed in literature or practice. This research aims to bridge this gap.

The objective of this research is to address the complexity in compliance assessment using an action-research (AR) methodology. “The purpose of AR is to build a theory within the context of solving an immediate practical problem in a real setting” (Azhar, Ahmad, and Sein 2009, 87-98). This research presents the outcomes of an action-research (AR) project undertaken with a top-tier global engineering and design consultants, Stantec Consulting Ltd., in the context of the design of a large healthcare facility. The objective of AR was to create a robust yet simple-to-use compliance assessment workflow, and simultaneously generate feasible and practically adaptable solutions to assist the design consultant in creating an automated BIM compliance assessment workflow for current and future projects. Three AR cycles were conducted over a span of 1 year to develop an optimized compliance assessment workflow. The key metrics for BIM compliance were identified, and evaluated over the course of this study.

An automated data analytics and visualization workflow was developed to simplify the compliance assessment process, thus reducing the complexity in compliance assessment caused by the inundation of data in digitally-enabled projects. Visual programming was used to automate BIM data analytics to represent key compliance metrics and streamline complex workflows. The interactive visualization aims to provide actionable information to project teams in a way that enables project experts to gain insights more effectively to inform design decisions and to help manage compliance with Owner’s BIM requirements. Various tools, for BIM-based model checks, BIM data management, etc., were investigated to support compliance assessment, and their applicability is discussed in this research. The BIM compliance process and BIM technology-related learnings from the case study project are also presented in this thesis.

## 1.2 Research Objectives and Methodology

The specific objectives of this research are to:

1. Develop an optimized technology-driven workflow for BIM data management to assure compliance with the Owner's BIM requirements.
2. Develop an automated workflow using visual programming language (VPL) to extract and parse data from BIM models to assess key performance metrics for compliance.
3. Use interactive data visualization analytics for BIM compliance assessment and facilitate informed decision-making, which can be leveraged by all the project stakeholders.

As the purpose of this study is to solve a practical problem that industry is currently facing and simultaneously create theoretical and conceptual knowledge, an action-research (AR) methodology was adopted due to its "proactive", "practical problem-solving interventionist approach" and to co-create solutions with academia and industry working together (Poirier, Staub-French, and Forgues 2015, 74-84). "The purpose of AR is to build a theory within the context of solving an immediate practical problem in a real setting" (Azhar, Ahmad, and Sein 2009, 87-98). The adoption of AR will enhance the researcher-practitioner collaboration to conduct research on compliance and decision-related problems and to serve with feasible and adaptable solutions (Poirier, Staub-French, and Forgues 2015, 74-84). Susman and Evered (1978, 582-603) discussed six characteristics of AR which are representative of the objectives and methods of practitioners.

1. AR is "future-oriented" as it is focused on creating a better and desirable future for the industry;

2. AR is “collaborative” in that it creates an interdependence between the practitioner and researcher particularly based on the needs of the practitioner and competencies of the researcher, hence directing a two-way research process.
3. AR implies “system development” by encouraging the development of appropriate structures required to build the necessary system and competencies to generate necessary communication and problem-solving procedures.
4. AR generates “theory grounded in action” as the action-based theory developed using this methodology is guided by theory and the consequences of the problems are evaluated at the face of the organization.
5. AR is “agnostic” as the researcher understands that the objectives and the method are generated from the process itself, and the consequences of selected actions might not be known ahead of time.
6. AR is “situational” because the relationships between the people, events, and things are not often invariant and can change as the situation changes.

In this study, the AR cycle developed by Susman and Evered (1978, 582-603) will be pursued. AR is a cyclical process that consists of five different phases (Susman and Evered 1978, 582-603; Baskerville 1997, 24-43; Azhar, Ahmad, and Sein 2009, 87-98; Poirier, Staub-French, and Forgues 2015, 74-84). The following five distinct phases of AR are the research activities carried out in this study, depicted in Figure 1.1.

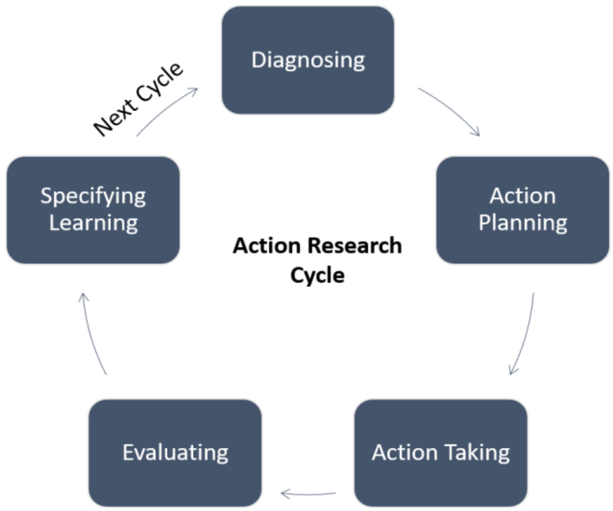



**Figure 1.1: AR cycle to address the objectives of this study, adopted from Susman and Evered (1978, 582-603)**

1. **Diagnosing**: The first activity consists of diagnosing the existing practices employed by the industry and identifying the opportunities for improvement to justify the need for change.
2. **Action Planning**: The second activity consists of planning the intervention and identifying the supporting tools required to approach the change effectively.
3. **Action Taking**: The third activity is to execute the planned action in the right setting.
4. **Evaluating**: The fourth activity is to study and evaluate the outcomes of the actions taken in the previous step. This evaluation must determine whether the approach employed to bring a change was successful or not.
5. **Specifying Learning**: The final activity of each AR cycle is to create new knowledge from ongoing evaluations. Learnings are specified at each phase of the AR.

Figure 1.2 below depicts the overall research roadmap with the relationships between different research activities carried out to achieve the objectives of this study, and the output of research outcomes.

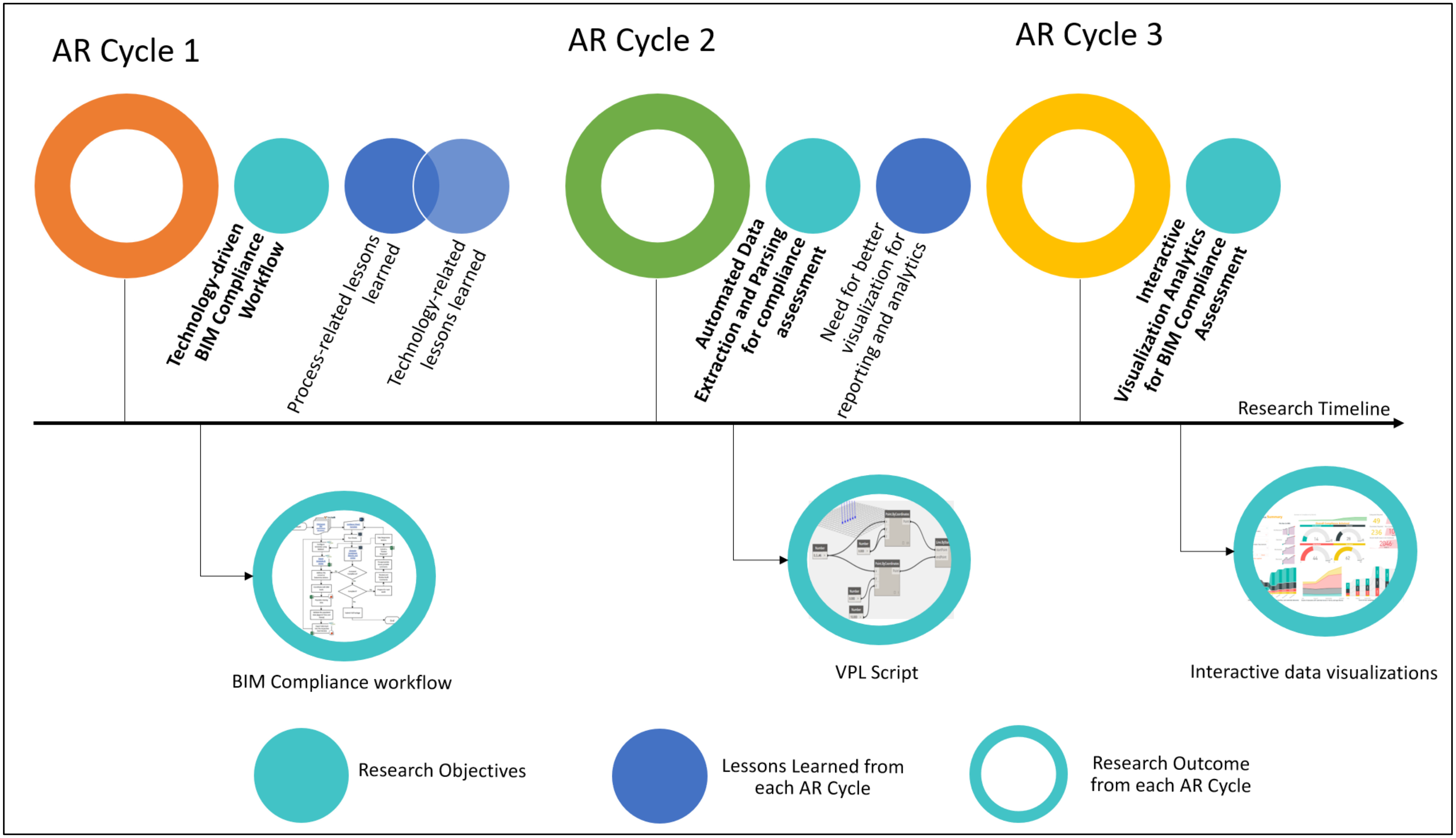



**Figure 1.2: Research roadmap showing the relationship of all research tasks and outcomes of each Action Research (AR) cycle**

## 1.3 Thesis Outline

This thesis consists of six chapters; Chapter 1 introduces this study and provides an overview of the research project by setting out the objectives and methodology employed by the Author. Chapter 2 presents the case study analysis and practical motivation of this research by outlining the necessary project information, industry’s current BIM quality review practices and the challenges observed in executing these practices. Chapter 3 provides an in-depth research background and identifies the existing knowledge gaps. Chapter 4 contains the main body of the thesis and provides the methodologies used to achieve the three objectives of this research. Chapter 5 serves as a conclusion to this research project, identifying the limitations of this work and future research opportunities.

## Chapter 2: Case Study Project and Practical Challenges

This chapter presents the motivation behind this research. Most of the work described in this thesis was conducted with Stantec, a top-tier global design and engineering firm, who were the design consultants on a healthcare project described below. The Author collaborated as a 'research intern' with the design consultants on the project for a period of 1 year and thus was actively involved in the process of compliance assessment with Owner's BIM requirements during the design phase. During this active involvement, the Author observed several inefficiencies in the process employed by the professionals, which served as the motivation of this research. The healthcare facility (shown in Figure 2.1) was procured using a design-build project delivery method. Table 2.1 is provided below to give a brief overview of the project along with the data collected for analysis in this study.

**Figure 2.1: 3D Rendering of the Healthcare Project (Source: Fraser Health, Project Photos Gallery, URL: [https://tinyurl.com/y78mjgnk](https://tinyurl.com/y78mjgnk))**

**Table 2.1: Project Overview and List of Data Analyzed**

| Project Parameters | Details |
|---|---|
| Project Type | Healthcare |
| Location | New Westminster, B.C., Canada |
| Budget | $ 260 Million |
| Project Schedule | February 2017 – December 2019 |
| Area | 36,000 $m^2$ |
| Delivery Method | Design-Build |
| Data Analyzed | • BIM Requirements Overview<br>• BIM Standards Requirements<br>• BIM Execution Plan (BEP)<br>• BIM Design Data and Geometry Specifications (DGS)<br>• BIM Model Review Protocol<br>• Coordination Meeting Minutes<br>• 3D Models from all disciplines |
| Level of Interaction with the Design Team | High Involvement – Bi-weekly progress meetings with the Design BIM team; Constant feedback from the Design consultant's Project Manager and the BIM leads on the project |
| Duration of Study | June 2017 – April 2018 |

**Summary of the Owner's BIM goals and requirements at the design phase:**

The Healthcare Authority or the Owner initiated a BIM process for all new capital projects, starting from this phase. The overall BIM goal defined by the Owner on this project was to *"utilize a BIM process to derive consistent digital data that can be used to drive downstream uses during the entire life cycle of the facility, from design, through construction and on into Facility Maintenance and Operations".* A high-level summary of some of the BIM goals identified and their implications for model authors are listed in Table 2.2.

**Table 2.2: High-level summary of BIM Objectives on this project**

| BIM Goal | Authoring Implications | Responsible Party |
|---|---|---|
| Access to Information during the Design Phase | Design and construction information input in a structured manner that allows evaluation of the Owner Project Requirements (OPRs). | Design Consultants/ Design-Builder |
| Data Harvesting for Facilities Maintenance and Operations Management | Designers will model elements to be tracked. Contractor and Trades will provide information against such elements | Design-Builder |
| Coordinated High-Quality Design | Ongoing virtual coordination and audit of design against agreed standards | Design-Builder |

A clear scope of work was laid out in the Project's BIM standards requirements, such as minimum modeling requirements, data requirements at different stages of the project, and list of objects that needs to be modeled for asset tracking during facilities maintenance and operations (FMO). In short, the intent is to design BIM for FMO (Figure 2.2).

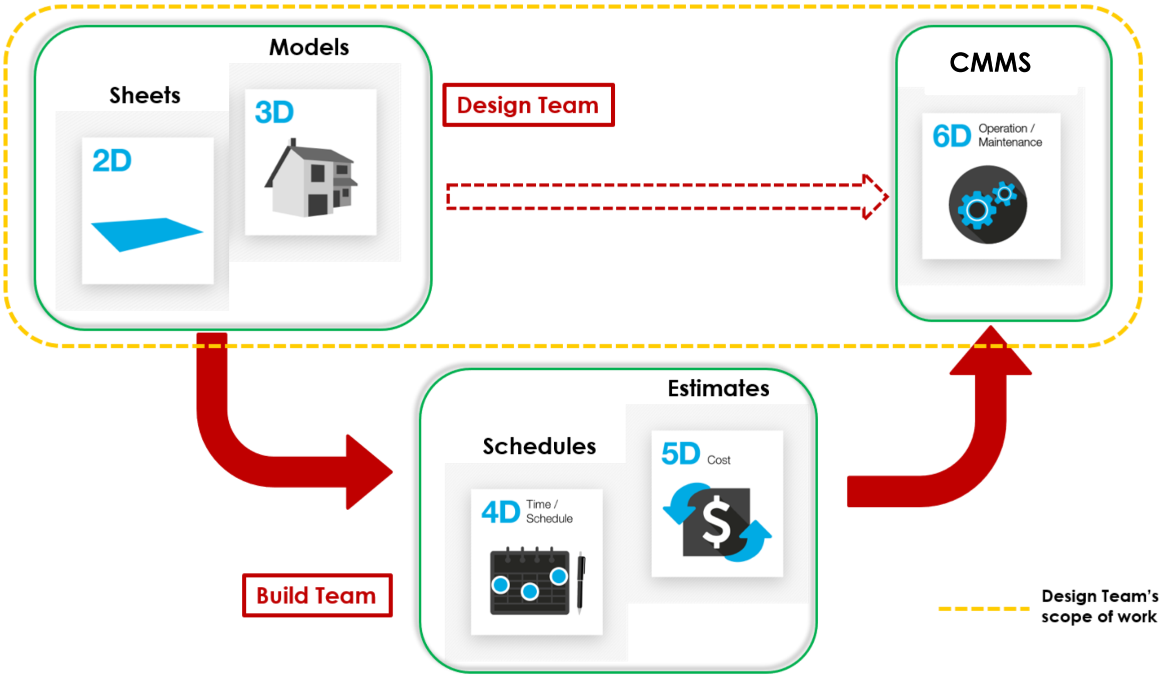



**Figure 2.2: BIM Dimensions and the Design Team's Scope of Work as implied in the Owner's Project Requirements**

A BIM consultant, hired by the Owner to fulfil their overall BIM goals, created the BIM requirements, which were extremely comprehensive and detailed. The Owner conducted two types of audits on a fixed schedule, and Figure 2.3 depicts the workflow employed by the team. The first audit started one month after the start of the project. A monthly (fourth week of every month) in-depth audit was conducted to check that the models and data comply with the Owner's BIM requirements. The Owner generated a report indicating issues of non-compliance and recommended best practices to solve such issues. Another monthly (second week of every month) audit was conducted to check whether the flagged issues are being resolved or not. Any requirements that were flagged where the design team wanted an exception approved were raised to the Owner, and any agreed resolution was recorded in the BEP. Issues were tracked and remained flagged until resolved. Non-compliance of the BIM requirements, as specified in the

BIM requirements documents, was considered as a failure to comply with the project requirements.

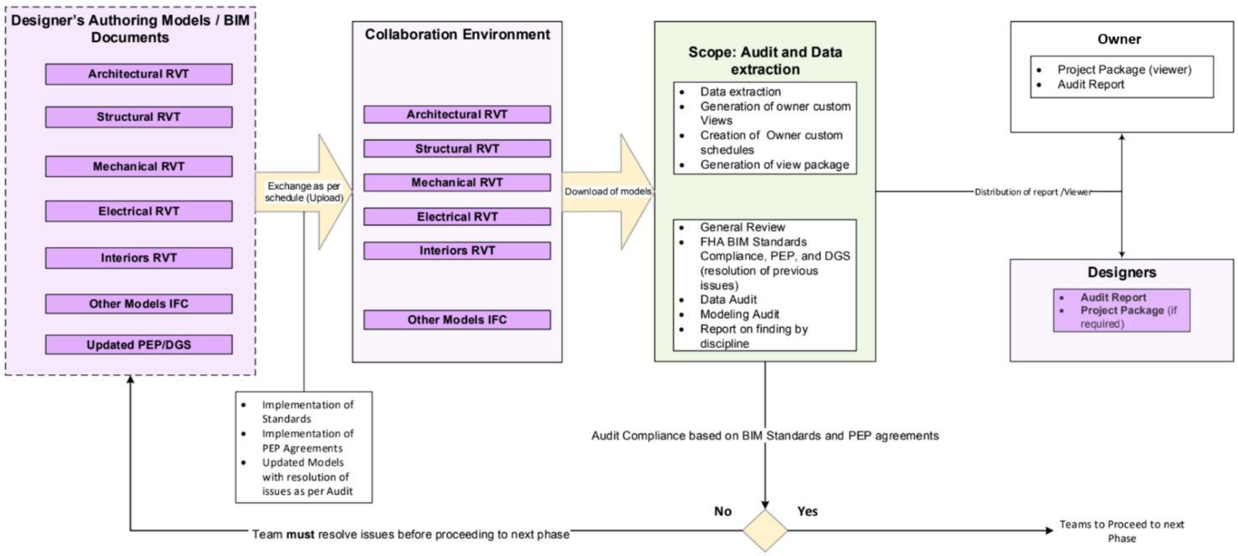



**Figure 2.3: BIM Model audits workflow for the design phase**

## Current BIM and data review practices:

The engineering and design company, Stantec, studied had a QA/QC process called “Model Review Process”. As written in the official documents, this process was created with the following three objectives:

- “Ensures that the BIM model is built in a quality method that supports the project and is in alignment with the project’s BIM Execution Plan (BEP),
- A clean, well-built model will perform more efficiently,
- Provide knowledge sharing - will help to spread good modeling practices throughout the company.”

The Model review process was broken down into three stages, as shown in Figure 2.4, and Table 2.3 summarizes the activities are carried out in each stage.

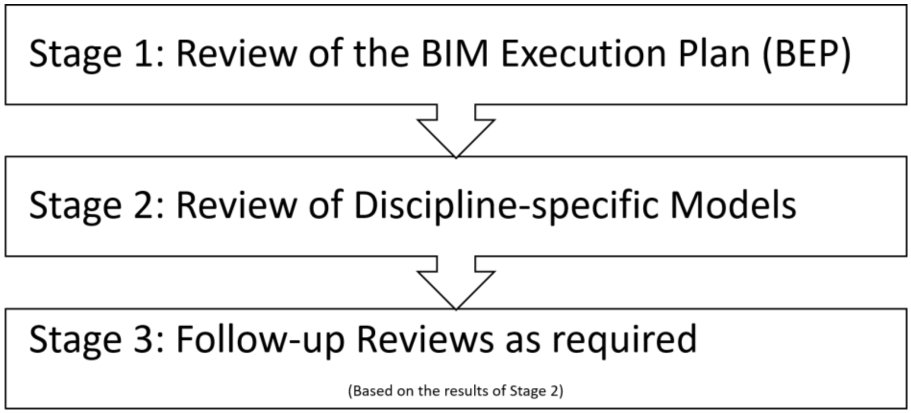



**Figure 2.4: Stages in Model Review Process during the Design Phase used by the Design Consultants**

**Table 2.3: Model review activities categorized over various stages by the Design Consultants**

| **Stages** | **Activities** |
|---|---|
| **Stage 1** | 1. Review Requested: PM requests Review once the first draft of project BEP is published.<br>2. Project Info: PM is sent an email to gather basic project information.<br>3. Team Discussion: Reviewer conducts a discussion with key members of the project team.<br>4. BEP Review: Reviewer reviews the BEP collected from the project team.<br>5. Report: Reviewer issues report of findings/recommendations to project team.<br>6. Findings Review: Reviewer conducts review meeting with the project team to go over their findings. |

| | |
|---|---|
| **Stage 2 & 3** | 1. Review Request: BIM Manager requests Review once audit milestone is achieved.<br>2. Discipline Discussion: Reviewer conducts a discussion with key members of the project team.<br>3. Model Review: Reviewer reviews the files collected from the project team.<br>    a. Perform Model Health Check (MHC)<br>    b. Based on the results of the MHC, perform a deeper dive on an as needed basis.<br>4. Report: Reviewer issues report of findings/recommendations to project team.<br>5. Findings Review: Reviewer conducts review meeting with the project team to go over their findings. |

A timeline to conduct the model reviews was generically fixed by the company, as shown in Figure 2.5.

| Stage 1 | Stages 2 & 3 | | |
|---|---|---|---|
| BEP | Arch | Struct | MEP |
| Before any models are started | Prior to the model(s) being used by another discipline to start their model(s)<br>-OR-<br>50% DD | Prior to exporting information to analysis<br>-OR-<br>75% of the current phase | 75% of the current phase |
| | WHICHEVER COMES FIRST | | |
| 2 - 4 Hours | 2 - 4 Hours per discipline | | |

**Figure 2.5: Timeline for Model Review Process created and used by the Design Team**

Based on the observations of the reviewer, a project fell into one of the three categories discussed in Table 2.4.

**Table 2.4: Model review process outcomes - color categorization of the results by the Design Consultants**

| Category | Status |
|---|---|
| **Green** | The project meets all the set criteria & appears to be on a solid footing to complete the project successfully.<br><br>These projects will not be reviewed again unless there would be a reason to believe that the team has not continued to work to a high level of quality:<br><br>• Complaints are made during a review of another discipline,<br>• Major staffing changes within the project team. |
| **Yellow** | The project meets most of the set criteria and appears to be on a reasonable footing to complete the project successfully once the Model Manager/CAD technician incorporates the comments made in the review.<br><br>These projects will not be reviewed again if:<br><br>• The model is a project deliverable,<br>• Project is a high-risk project,<br>• Input from the review with another discipline. |
| **Red** | Project fails to meet the set criteria and appears to be in danger of not completing the project successfully.<br><br>A BIM expert will help the team get the project back on track, |

| | |
|---|---|
| | These projects will be reviewed again<br><br>• At 75% if in the final project phase,<br>• Again at 50% completion of the next project phase,<br>• Prior to any model submission if the model(s) is a deliverable. |

Even though a generalized 'Model Review Process' was in-place, it was observed that for a large number of projects, the process was entirely dependent on the Model Manager and the BIM Manager's discretion. They pursued whatever it took to get the project done. Process delegation was entirely dependent on the level of expertise of the individual users on a project, combined with the project manager's willingness to allow the users to clean up the model(s), along with their sophistication in understanding the kind of effort required to maintain healthy models.

## 2.1 Challenge 1: Information Quality (IQ) Issues

This section provides examples of poor information quality as a testament to not having any provisions in the existing model review process of the organization under study. Even though the Owner's BIM requirements were specified to provide complete, consistent, accurate, and interpretable information, we observed various instances of non-compliance to these requirements. No provisions or recommendations were made to ensure high quality of data in the model review process employed by the project team. The examples provided below depicts the instances of non-compliance with the Owner's non-graphical (or parametric) information requirements on this project.

### 2.1.1 Incompleteness

In our analysis, incompleteness is assessed by investigating the missing information in the BIM models in comparison with the Owner's BIM requirements. At the end of the design phase of the project, a considerable proportion of design information was found missing in the BIM models. Figure 2.6 depicts the completeness of required design information at the end of the design phase, as analyzed by the Author:

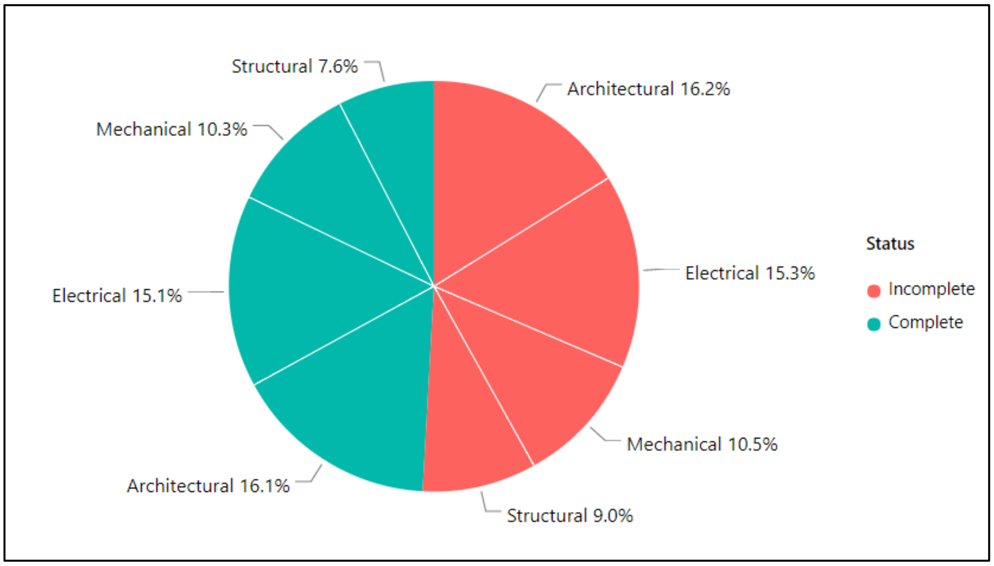



**Figure 2.6: Percentage of Completeness of Required Design Data at the end of Design Phase**

Critical information like OmniClass Number (system table 23) classification was found significantly (over 50%) incomplete (See Figure 2.7 and Figure 2.8) across all disciplines despite being required by the Owner at the end of the design phase. This classification system is a critical piece of information that is used to control the data and document collection during the design and construction phase, and support information transfer to the Owner's CMMS system at the handover phase. Similar issues concerning the incompleteness of other critical information were also observed.

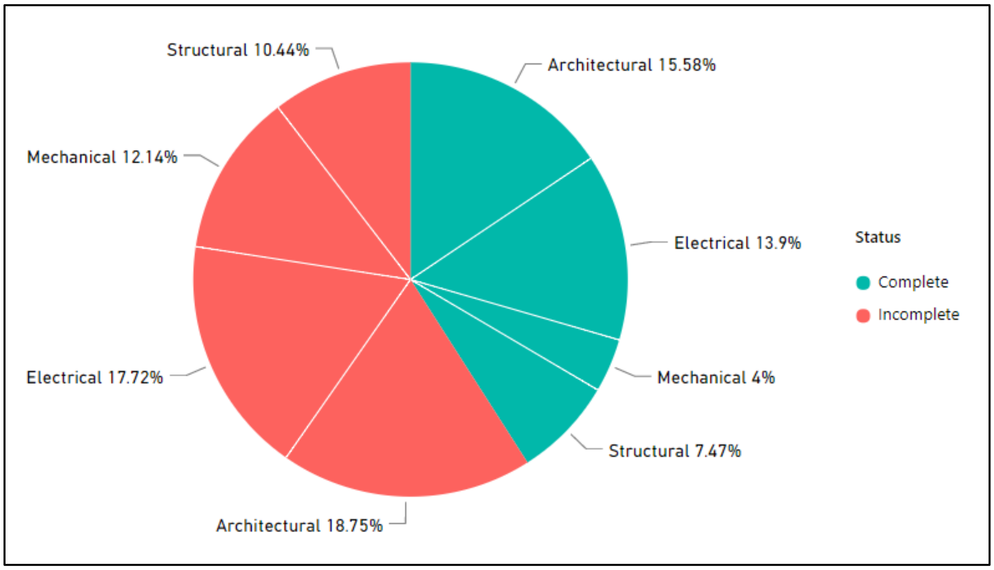



**Figure 2.7: Percentage of completeness of required OmniClass Number (system table 23) at the end of the design phase**

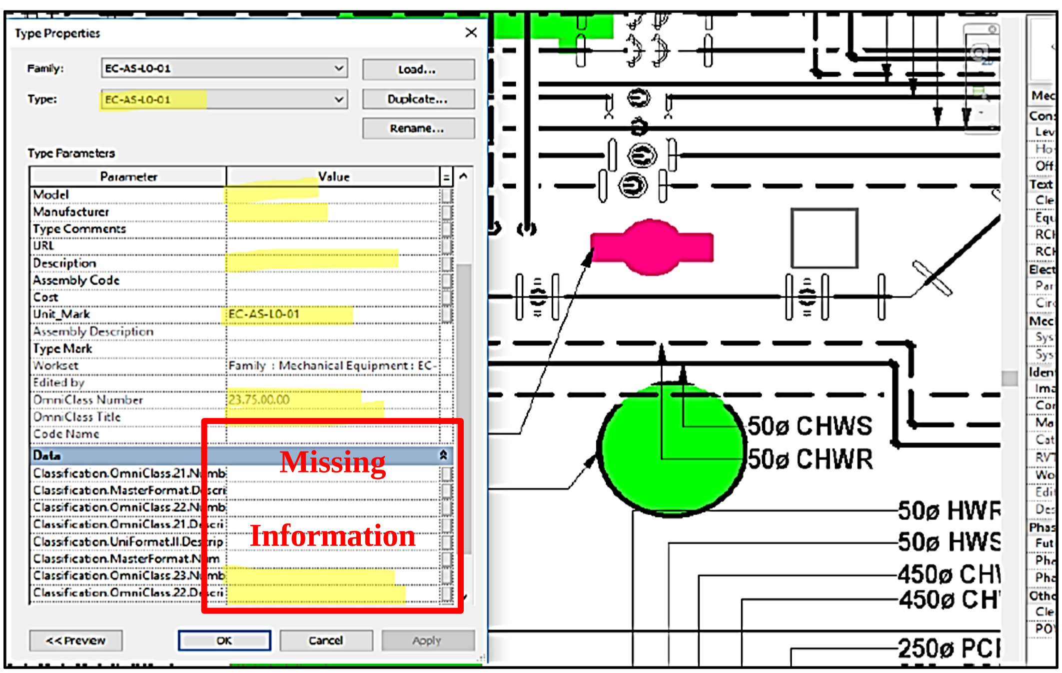



**Figure 2.8: Missing classification system information at the end of the design phase**

### 2.1.2 Inconsistency (Contradiction and Duplication)

In the literature, inconsistency refers to different aspects of the data and can be related to the value, representation, or physical representation of data (Wand and Wang 1996). Wand and Wang (1996) defined inconsistency as different data values that occur in the same state of information matching a state of the real system, whereas Zadeh et al. (2017) define inconsistency as a state of representing ambiguous and duplicate information in the model. In our analysis, we define inconsistency as the duplication and contradiction of the information values assigned to an object in the BIM model.

Figure 2.9 (left) shows the contradiction in the Fire Rating values assigned to a Wall family type. Fire rating value of 0 hour (“0 HR FRR”) is assigned to the Wall type name whereas the type parameter shows a Fire rating of “1 Hour”. Figure 2.9 (right) shows the duplication of the Owner’s parametric requirements in the BIM. Numerous examples related to the duplication and contradiction of the information values were found across the building information models. The issue of contradiction can be relatable to the modeling practices employed by the BIM user, and the fact that information, such as fire rating, is being entered next to the object type’s name and not the in-built parameter already provided by recent BIM authoring tools, such as Autodesk Revit and ArchiCAD. These inconsistencies in the information provided by the project team might lead to different versions of truth for the consumers of this data.

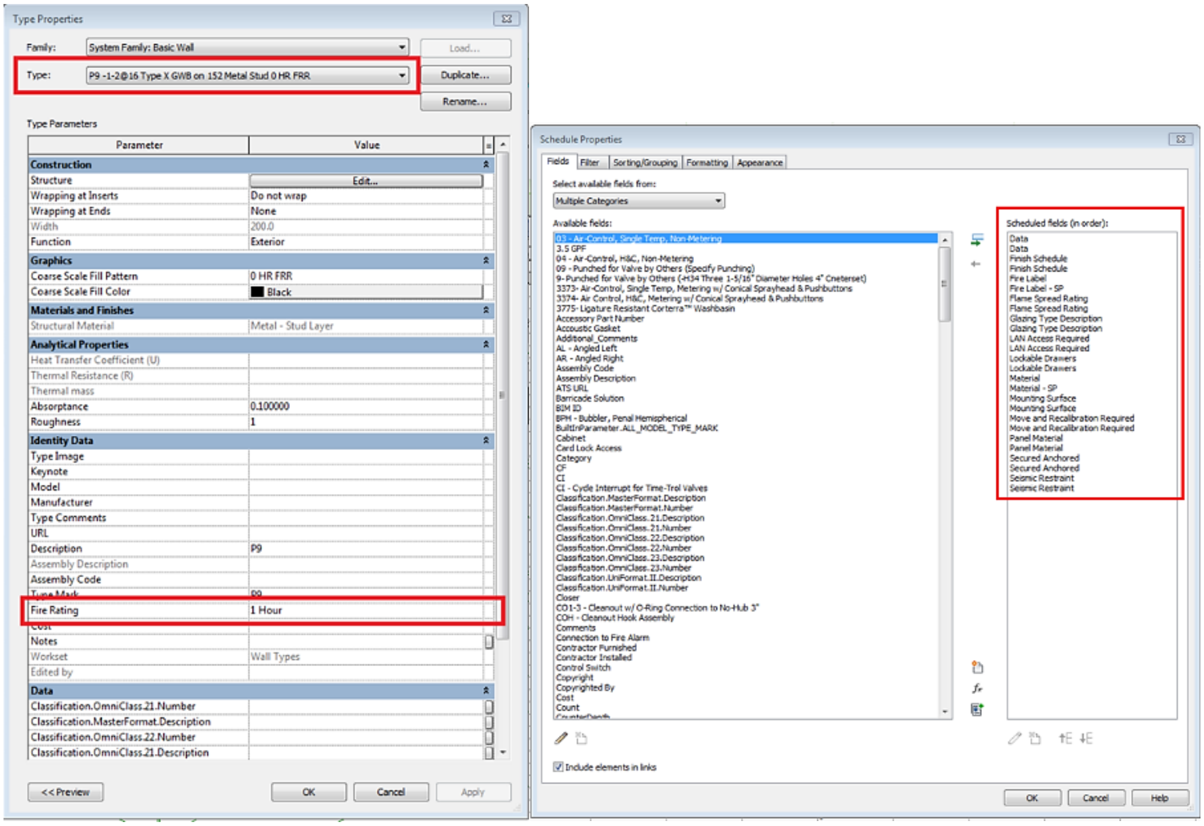



**Figure 2.9: (Left) Contradiction in Fire Rating Value - "0 HR FRR" in the Type Name and "1 Hour" in the Fire Rating Parameter; (Right) Duplication of Instance and Type-based Parameters in the Architectural BIM**

### 2.1.3 Understandability

Wang and Strong (1996) describe understandability as the ease of understanding and interpreting the information. Assaf and Senart (2012) describe it as the information that is understandable to humans and facilitates easy consumption by conveying logical meaning. In our analysis, information understandability facilitates the ease of interpretation by the information consumer irrespective of their knowledge and experience (P. A. Zadeh et al. 2017).

A clause was identified in the 'Naming convention of data' section of the Owner's BIM Standards stating that the naming of the elements should "reflect an easily recognizable description. Use of company's name tag, "standard", "generic", and "default" is prohibited". We identified various discrepancies during our investigation. Apart from these restricted terms, we noticed an abusive usage of prefix "PLC" that is used in the project as a placeholder element. A placeholder element may be something that has not yet been designed but is included so that it may be switched out for a designed element at a later date. At the end of the design phase, "PLC" was present excessively over the project thus causing ambiguity in the design status and possible confusion regarding design state among design consultants and others accessing model information. Figure 2.10, Figure 2.11 and Figure 2.12 depict the issue. Mechanical equipment is one of the valuable assets that is tracked by the facility Owner on this project and thus, it is important to comply with the requirements. Issues discussed in the examples below are identified concerning mechanical equipment.

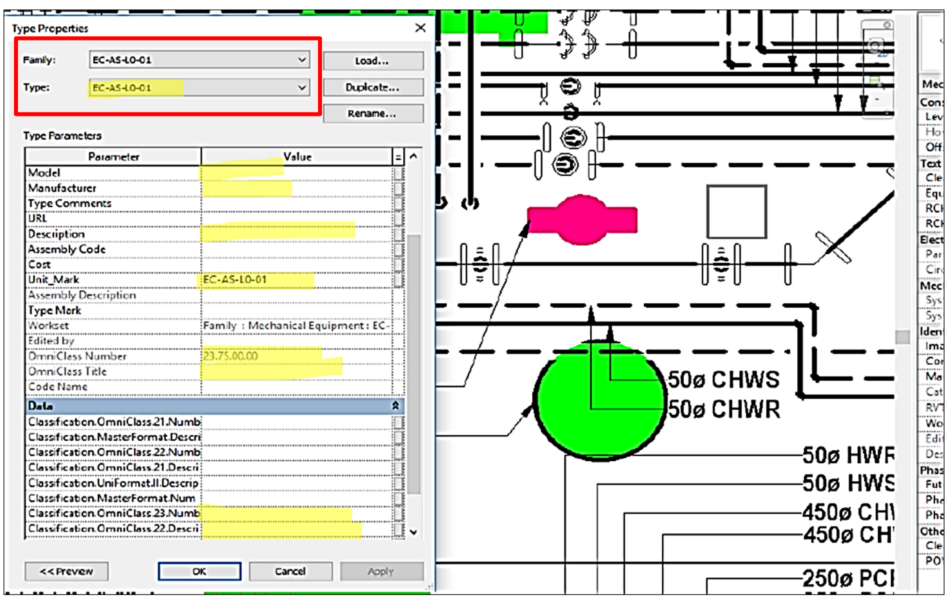



**Figure 2.10: Lack of descriptiveness in the element name "EC-A5-CO-01", which affects the understandability of information during downstream uses.**

| Category | Family Name | Type Name |
| --- | --- | --- |
| Electrical Equipment | Electrical Equipment - plc & HMI | EQP - plc & HMI GEN. BUS#1 |
| Detail Items | P-Schem Power Logic | P-Schem plc |
| Mechanical Equipment | plc_silencer_SL-A | plc_silencer_SL-A |
| Mechanical Equipment | plc_silencer_SL-B | plc_silencer_SL-B |
| Mechanical Equipment | plc_silencer_SL-A | plc_silencer_SL-A 3 |
| Mechanical Equipment | plc_silencer_SL-A | plc_silencer_SL-A 4 |
| Mechanical Equipment | plc-fuel_oil_tank_steel | plc-fuel_oil_tank_steel |
| Mechanical Equipment | plc_Fuel_OIL_fill | plc_Fuel_OIL_fill |
| Mechanical Equipment | plc_fuel_oil_entry_sump | plc_fuel_oil_entry_sump |
| Mechanical Equipment | plc-fuel_oil_tank_steel | plc_fire_rated |
| Mechanical Equipment | plc_fuel_polishing | plc_fuel_polishing |
| Mechanical Equipment | plc_silencer_SL-B1 | plc_silencer_SL-B1 |
| Mechanical Equipment | plc_fuel_oil_day_tank_rect | plc_fuel_oil_day_tank_rect |
| Mechanical Equipment | plc_blowdown-heat-recovery | plc_blowdown-heat-recovery |
| Mechanical Equipment | plc_blowdown-seperator | plc_blowdown-seperator |
| Mechanical Equipment | plc_heat_trace_mech | plc_heat_trace_mech |
| Stairs | Assembled Stair | plc_Stair-Metal |
| Mechanical Equipment | plc_flash-seperator | plc_flash-seperator |
| Mechanical Equipment | plc_steam_silencer | plc_steam_silencer SP-5-24 |
| Mechanical Equipment | plc_heat_trace_mech | plc_heat_trace_mech |
| Roof Soffits | Roof Soffit | plc - Exterior Soffit |
| Ceilings | Compound Ceiling | plc-Suspended GWB on Track - Runners |
| Wall Sweeps | Wall Sweep | plc_Fin_50x200_Yellow |
| Walls | Basic Wall | plc_LKMe_1 |
| Walls | Basic Wall | plc_Alucobond_Blue |

**Figure 2.11: Placeholders or "PLC" found in critical Mechanical Equipment at the end of the design phase, representing that the element might change at a later stage but the Owner needs to track the asset for procurement**

| Category | Family Name | Type Name |
| --- | --- | --- |
| Pipe Accessories | plc-Valve - Balancing - Dynamic | standard |
| Pipe Accessories | PLC-Valve - Gate | standard |
| Pipe Accessories | plc-Valve - Balancing - Dynamic | standard |
| Mechanical Equipment | plc-Medical Gas - Zone Valve Box - 3 Gases | standard |
| Mechanical Equipment | plc-Medical Gas - Zone Valve Box - 4 Gases | standard |
| Pipe Accessories | plc-Valve - Check | standard |
| Sprinklers | plc-Fire - Sprinkler - Concealed | standard |
| Pipe Fittings | plc-Cleanout_inline_single | standard |
| Windows | PLC_Generic Exterior Fixed Window | 2100Hx1300W - standard Glazing |
| Windows | PLC_Generic Exterior Fixed Window | 1800Hx1500W - standard Glazing |

**Figure 2.12: Vague and unclear "Standard" naming convention used, but the usage is restricted as per the Owner's BIM requirements**

### 2.1.4 Inaccuracy

As discussed by Solihin et al., (2015a), information inaccuracy has wide meaning and can result from all the IQ issue types discussed above. From an FM perspective, lack of understandable information can result in incorrect or inaccurate information. The same interpretation can be applied to information incompleteness and inconsistency. Based on the similar discussion, we assess the information accuracy by confirming the “values, geometries, relations, and spatial information of the objects in the model concerning the requirements” (Y. Lee, Eastman, and Lee 2015; P. A. Zadeh et al. 2017). Figure 2.13 explicitly shows the inaccurate representation of the Room Area. Some rooms appeared to be redundant or not enclosed. In these cases, the area information is not reliable and affects the Owner’s space program.

<Room Schedule>

| A | B | C |
|---|---|---|
| Name | Number | Area |
| Chiller | EC1006 | Not Enclosed |
| Elev 23 | ELV23-EC | Not Enclosed |
| Mech | EC1028 | Not Enclosed |
| Vestibule | PK2011 | Not Enclosed |
| Stair | STR01-PK2 | Not Enclosed |
| DC Power & Battery | ELEC 1041a | Not Enclosed |
| Service Corr | CORR04-EC | Not Enclosed |
| Stair Vest | PK3069 | Not Enclosed |
| Vest | PK2067 | Not Enclosed |
| Vest | PK1067 | Not Enclosed |
| Vest | PK2067 | Not Enclosed |
| Vest | PK1067 | Not Enclosed |
| Vest | PK3067 | Not Enclosed |
| Fuel Oil Pump Room | PK3090 | Not Enclosed |
| Mech | PK1005 | Not Enclosed |
| Corr | CORR02-EC | Not Enclosed |
| Corr | CORR03-EC | Not Enclosed |
| Vest | EC1045 | Not Enclosed |
| Med Gas | EC1019A | Not Enclosed |
| Mech | EC1053 | Not Enclosed |
| Service Area | EC1017c | Not Enclosed |
| Process Water | EC1022 | Not Enclosed |
| Process Water | EC1024 | Not Enclosed |
| Elec | EC1041 | Not Enclosed |
| Elec | EC1039 | Not Enclosed |
| Elev 21 | ELV21-PK1 | Redundant Room |
| Hamper | 2136 | Redundant Room |
| Patient Bed | 2125 | Redundant Room |
| Patient Bed | 2139 | Redundant Room |
| Stair | STR05-04 | Redundant Room |
| Elev 21 | ELV21-PK2 | Redundant Room |
| Elev 21 | ELV21-PK3 | Redundant Room |
| Stair | STR04-02 | Redundant Room |
| Shaft | SFT07-02 | Redundant Room |
| Shaft | SFT06-04 | Redundant Room |
| Elev 21 | ELV21-01 | Redundant Room |
| Stair | STR05-01 | Redundant Room |
| Stair | STR04-03 | Redundant Room |
| Elev 23 | ELV23-03 | Redundant Room |
| Shaft | SFT06-03 | Redundant Room |
| Vest | 5125 | Redundant Room |
| Elev 21 | ELV21-EC | Redundant Room |
| Shaft | SFT11-02 | Redundant Room |
| Roof | ROOF03-03 | Redundant Room |
| Stair | STR05-02 | Redundant Room |
| Shaft | SFT07-04 | Redundant Room |
| Staging | 5010 | Redundant Room |
| Stair | STR05-05 | Redundant Room |
| Stair Vest | 5011 | Redundant Room |
| Storage | 5037 | Redundant Room |
| Shaft | SFT14-03 | 0.43 m² |
| Shaft | SFT14-02 | 0.45 m² |
| Shaft | SFT14-04 | 0.48 m² |
| Shaft | SFT02-02 | 0.75 m² |
| Shaft | SFT02-04 | 0.75 m² |

**Figure 2.13: "Not Enclosed" and "Redundant" rooms identified in the BIM models at the end of the design phase, affecting the Owner's space requirements and space planning**

## 2.2 Challenge 2: Complexity of BIM and Data Quality Assessment

The Author witnessed various inefficiencies in the model review practices, information quality issues, and issues faced by the project teams to drive their decisions related to the management of BIM. The following sections provide examples representing typical issues related to model review process employed by the project team. These examples focus on the identification of obstacles in establishing methods for BIM management and the challenges in utilizing delivered BIM data in the construction and operations phases of the building.

To effectively evaluate the project performance and compliance requirements for the downstream information consumers such as facility managers and Owners, it is essential to assess the BIM model quality (or its health) and information quality (P. A. Zadeh et al. 2017). Hence, the observed inefficiencies are attributable to the following two core areas of BIM:

1. **BIM Health**

   The health (or quality) of BIM represents the modeling practices employed by the project teams, and the graphical representation of 3D elements in BIM. For example, BIM warnings, file size, in-place families, mass elements, model groups, etc.

2. **BIM Information Quality**

   BIM information quality deals with the representation and accuracy of non-graphical data in BIM. For example, data incompleteness, understandability, inaccuracy, etc.

### 2.2.1 BIM Health Review Practices

A BIM expert reviews the modeling practices employed by the project teams. The results of this in-depth review of BIMs represents the BIMs ‘health.’ Even though the production of healthy BIM models is not specified in the Owner's BIM requirements, it is important to employ good modeling practices and deliver quality BIM models. "Particularly from the FM perspective, developing and maintaining the models are important. FM users, as the downstream information consumers, are very dependent on the quality of modeling in the previous phases" (P. A. Zadeh et al. 2017).

To evaluate the model performance, a BIM expert reviews the model health bi-weekly and distributes the results with the project team, typically with only CAD technicians, highlighting the areas that might need improvement. The improvements are then reflected in the successive model health reviews and the progress is manually tracked. We analyzed the model health review process and QC reports on this project and observed the following inefficiencies:

### 2.2.2 Tedious Execution Process

Even though this model health review process is very critical to evaluate and control the performance of model-based projects, its execution is perceived to be very tedious. The figures below briefly show the exhaustiveness of the information that needs to be manually extracted from BIM models to represent the model's health status. Through an informal interview with the Lead BIM Manager on this project, we found that <u>it takes a BIM Expert about two days to manually extract this information from just one BIM model</u>. The project under study has six models categorized based on the discipline and building system type, for example, Architectural Exteriors (Shell), Architectural Interiors (Fitout), Mechanical Plumbing, Mechanical HVAC, etc. As a result, a BIM expert needs to invest about twelve working days per every BIM model health review. We also observed a lack of knowledge about the available technologies to extract the required information automatically from the BIM models among the project's BIM team.

Therefore, the extent of manual progress tracking and the extensive time required for information extraction and review processes makes this BIM model health review workflow a tedious process.

**Revit Model QA/QC Review**

| Project Information | | | |
|---|---|---|---|
| Project Name: | Brentwood | Reviewer: | Aubrey Tucker |
| Project Number: | 144312117 | Date of Review: | 2015-03-16 |
| Project Manager: | Laurenz Kosichek | Current Project Phase: | Construction Documents |
| Model Manager: | Usman Aziz | | |

| Model Information | | | |
|---|---|---|---|
| File Name: | SAL_ARCH_BTC_PHASE ONE_C | Model Discipline: | Architecture |
| File Size: | 568 MB | Discipline Model Manger: | Usman |
| Template Used: | Basic Stantec Arch | Issue Date of Drawings: | Ongoing |

**Model Manager's Comments**

The implementation of the BIM Execution Plan could have been followed consistently from the beginning of the project but in its draft stage it fell in priority to the time sensitivity of project milestones. It has been finalized and being implemented by all disciplines.
- When the team was at its largest at BP, it consisted of various Revit skill sets. Again due to time constraints and volume of work, the quality of modeling took a toll.
o Misuse of room separation lines
o Walls spanning multiple floors.
o Misuse of models lines and detail lines
o Detail groups being created of one-time use instance
o Stairs needed to be re-worked in numerous of times
- Some of the items above can also be found in the "Warnings" list also with the common warning in the project "slightly off axis", this is due to the existing mall that is 0.12 degrees off 45. So anything aligned/related to the exiting mall tallies a warning.
- Early in the project we had some discussion to split the model. I had suggested that when the model reaches the 300mb point I will assess the performance of the model and make a decision to split. Currently the model hovering around 650-700mb the performance is still very good and will work through the job with the single model with regular maintenance.

**3D view of model**

Paste a screen capture of the default 3D view here:

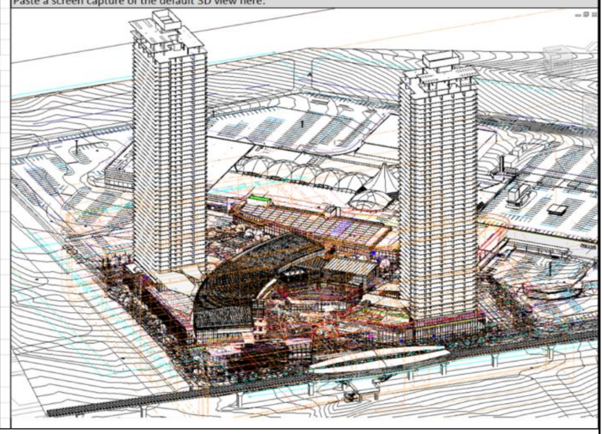


**Figure 2.14: Manual BIM Model Health Review - Project Information and Model Manager's Comments on the Areas of Improvement**

**Revit Model QA/QC Review**

**Model Health Stats:** (must be completed for all Projects)

| Item | Value (if applicable) | Comments |
|---|---|---|
| Number of Warnings: | 3462 | Significant amount of warnings due to lines being slightly off axis. Having the models broken up and with the project plan north being straight up w |
| Project Browser is well Orginized: | Is not | There is no organization of the project browser. All veiws are organized by view type. |
| Uses separate Modeling and Documentation Views: | Partially | There doesn't seem to be a consistent representation for views on sheets and views for modeling. Excessive amount of views are present, much clea |
| Number of Schedules: | 100 | Many schedules for each of the "tiles" in the project. |
| Number of Drafting Views: | 337 | |
| Number of Linked / Imported CAD Files: | 33 | |
| Number of Revit Links: | 9 | |
| Number of Imported Images: | 28 | |
| Uses Worksets: | Yes | 33 Worksets. Could have been optomized had the model been broken up |
| Uses Groups: | Yes | Model groups are primarily used for furniture content. No groups for modeling the architecture. |
| Uses Design Options: | Seldom | Only two instances remain of design options, this could also be because the project is in CD and not |
| Percent of Views with an assigned View Template: | 60% | 2509 total views with 1504 views with VTs. |
| Uses Phasing: | Yes | Moderate use of phasing, only the existing building is in the existing phase. No use of phasing view graphics. |
| Uses Revit Keynotes: | No | |
| Number of Unused Items | 1680 | File size of 568,851 KB before purging. |
| File Size after Purge: | 534,606 KB | |

**Figure 2.15: Manual BIM Model Health Review: Model Health Stats with Comments**

**Architectural Model Deep Dive**

| Category | Model Characteristic | Assessment: Major Improv't | Minor Improv't | Shows Mastery | N/A | Comments |
|---|---|---|---|---|---|---|
| **Project Settings & Standards** | | | | | | |
| | Adherence with Stantec (or Client) standards. | | | | X | |
| | Shared Coordinates | X | | | | Buildings should have been separated and coordinates shared fro |
| | Areas and Area Schemes | | | X | | |
| | Room Volume Calculation | | X | | | Rooms are overlapping in many cases due to not being confined p |
| | Sub-Categories | | | X | | Could be cleaner but functional. |
| **Datum Elements** | | | | | | |
| | Levels | | | X | | |
| | Grids | | X | | | Having grids slightly off axis is problematic, separated models sh |
| | Scope Boxes | | X | | | Seemed to be overused but possibly needed all. |
| | Reference Planes | | | X | | Perhaps under utilized but used none the less. |
| **Modeling & Geometry** | | | | | | |
| | Elements are in the Correct Category | | X | | | Found instances of ramps being made from floors, and curbs bein |
| | Over modeling / Under modeling | | X | | | |
| | Model Scope (are the models broken it appropriate chunks / uses) | X | | | | The model is one single model for three buildings, this should hav |
| | Massing Tools | X | | | | Not used. |
| | Unconnected Walls | X | | | | Many over lapping walls and unjoined corners. |
| | Attached Walls | | X | | | Many walls that should be attached are not and vice versa. |
| | Walls with edited profiles | | X | | | Unnecessary profile control, could have used other modeling opti |
| | Openings | | X | | | Openings being used for doorways and shape control. |
| | Rooms | X | | | | Overuse of room separation lines, rooms are suffering. |
| **Documentation & Views** | | | | | | |
| | Dependent Views | | | X | | |
| | View Depth | | | X | | |
| | Tags | | X | | | Overuse of tag types, redundant tags. |
| | Detail Lines | | | X | | |
| | Filled Regions | | X | | | Unfortunately, have to be used in detail views due to sloppy mode |
| | Visibility of Room Separation Lines | | X | | | Generally, good use. Excessive use needs to be fixed. 1922 of the |
| **Constraints** | | | | | | |
| | Pinned Elements | | | X | | inconsistent use but displays some users are utilizing |
| | Locked Dimensions | | X | | | seldom use |
| | Equality Constraints | | X | | | seldom use |
| **Families** | | | | | | |
| | In-Place Families | | | X | | |
| | System Families | | X | | | Redundant typing. |
| | Use of CAD geometry in Families | | | | X | |
| | 2D vs 3D Families | | | X | | Majority of content is 3D with 2d detailing |
| **Data** | | | | | | |
| | In-Place Families | | | | X | Could have but no need; typically site content |
| | System Families | | X | | | Again with the redundant typing. |

**Figure 2.16: Manual BIM Model Health Review: Review Outcomes based on Model Characteristics**

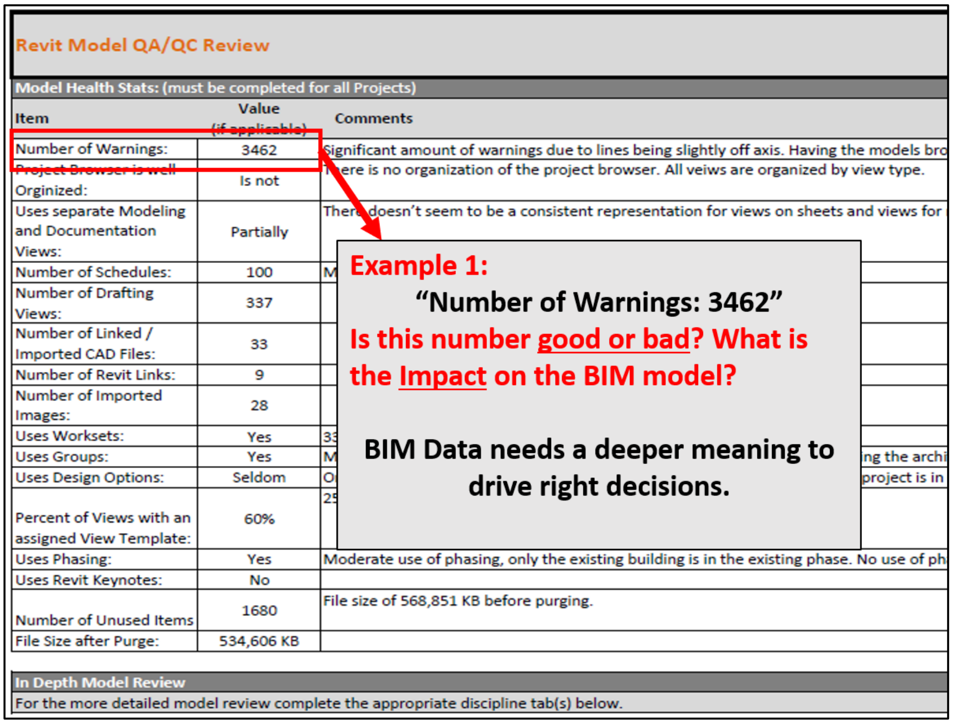
| Revit Model QA/QC Review | | |
|---|---|---|
| **BEP Review** | | |
| **Item** | **Y/N** (if applicable) | **Comments** |
| Project Agreements are in place and are coordinated with the BEP | N | Agreements were in the BEP but they were not coordinated effectively. |
| Project Deliverables are Defined | Y | |
| Project Team is Defined | Y | Firm players are defined. |
| Owner Stanted Requirements are Referenced | N/A | |
| BIM Uses are defined and approprite to the Project Requirements. | Y | |
| Model Content requirements are defined and approprite to the stated BIM uses. | N | Worksets were defined and ignored/not fullfilled by others. Shared models have to be modified each time to follow the workset r |
| Required Software products and versions are defined. | Y | Mandated 2013 and was fine after the first sharing. |
| File Transfer Protocols are established | Y | Project FTP site was used. |
| Model QA/QC Procedures are defined. | N/A | Being defined as we write this. |
| Supporting documents are completed to an approprite level based on the project schedule. | Y | Appendix of BEP explains. |
| **Basic BEP Info** | | |
| Location of Project BEP: | Y | \\CD1200-F03\workgroup\1443\active\144312117\06_dwg\6-02_sd\BEP |
| Date BEP was published to Project Team: | 1/29/2015 | Draft happened early. Posted officially very late in project. No signatures of agreement. |
| Date BEP was last edited: | 1/29/2015 | Due to lack of corporate structure and means/methods on starting BEPs there was not a good guidline for this project. |

**Figure 2.17: Manual BIM Model Health Review: BEP Review and Comments**

Due to these challenges, the frequency of this project's model health reviews was observed to be reduced significantly. Typically, the status of BIM model health and related improvements were communicated to the project team about a month before every design package submission to the Owner. But we found that the BIM model health was reviewed only once during the entire design development phase of the project, scheduled for twelve months. Hence, BIM models were developed over the entire design phase of the project without evaluating its performance and health.

### 2.2.3 Vague Reporting Structure

After analyzing the information that is extracted from models and entered manually in a spreadsheet by the BIM experts, we sensed a need to have a deeper meaning assigned to this information to inform decisions. Currently, the information extracted from the models is presented as mere ‘numbers’ in the spreadsheet. The impact of a particular ‘number’ on the model’s performance or the relative meaning of the information extracted is unknown to the project team. Figure 2.18 gives an example of this issue.



Revit Model QA/QC Review

Model Health Stats: (must be completed for all Projects)

| Item | Value (if applicable) | Comments |
|---|---|---|
| Number of Warnings: | 3462 | Significant amount of warnings due to lines being slightly off axis. Having the models bro |
| ~~Project Browser is well~~ Orginized: | Is not | There is no organization of the project browser. All veiws are organized by view type. |
| Uses separate Modeling and Documentation Views: | Partially | There doesn’t seem to be a consistent representation for views on sheets and views for |
| Number of Schedules: | 100 | M |
| Number of Drafting Views: | 337 | |
| Number of Linked / Imported CAD Files: | 33 | |
| Number of Revit Links: | 9 | |
| Number of Imported Images: | 28 | |
| Uses Worksets: | Yes | 33 |
| Uses Groups: | Yes | M ... ng the archi |
| Uses Design Options: | Seldom | O ... project is in |
| Percent of Views with an assigned View Template: | 60% | 25 |
| Uses Phasing: | Yes | Moderate use of phasing, only the existing building is in the existing phase. No use of ph |
| Uses Revit Keynotes: | No | |
| Number of Unused Items | 1680 | File size of 568,851 KB before purging. |
| File Size after Purge: | 534,606 KB | |

In Depth Model Review

For the more detailed model review complete the appropriate discipline tab(s) below.



**Figure 2.18: Manual BIM Model Health Review Stats with Unclear Impacts on the Health of the Model**

In the example provided above, BIM authoring tool, Autodesk Revit Warnings are used to demonstrate this issue of vagueness. Warnings are the messages that pop up while 3D modeling a project, notifying the deviations from the expectations. Autodesk[1] has stated that “Some warnings can be ignorable but many can cause issues with speed, stability, and accuracy in BIM models”. Unresolved warnings can impact the model performance, and it is

[1] Modelical Best Practices in Revit: Warnings and Model Performance. Retrieved on May 04, 2018. URL - https://www.modelical.com/en/gdocs/warnings-and-model-performance/

recommended by the Author of the tool to resolve the warnings as soon as they arise. At the end of design, 3462 count of warnings were reported. The impact of the warnings was not reported. There might be an instance where all the warnings can pose severe impacts on the modeled elements, or might be completely ignorable.

### 2.2.4 BIM Data Intensiveness

The widespread adoption of BIM and the data intensiveness in the models has further induced complexity in BIM management. The project under study had a sophisticated set of design BIM requirements to support the construction and operations of the facility. After checking the BIM models, we estimated over 950,000 data points in the models at the end of the design stage that would likely support the Owner's overall BIM goals. Figure 2.19 and Figure 2.20 shows the overview of the count of data values categorized by each discipline. Considering limited information management skills in the AECOO industry, handling the requirements on this project turned into an information management problem. The design team faced serious quality management issues (discussed below).

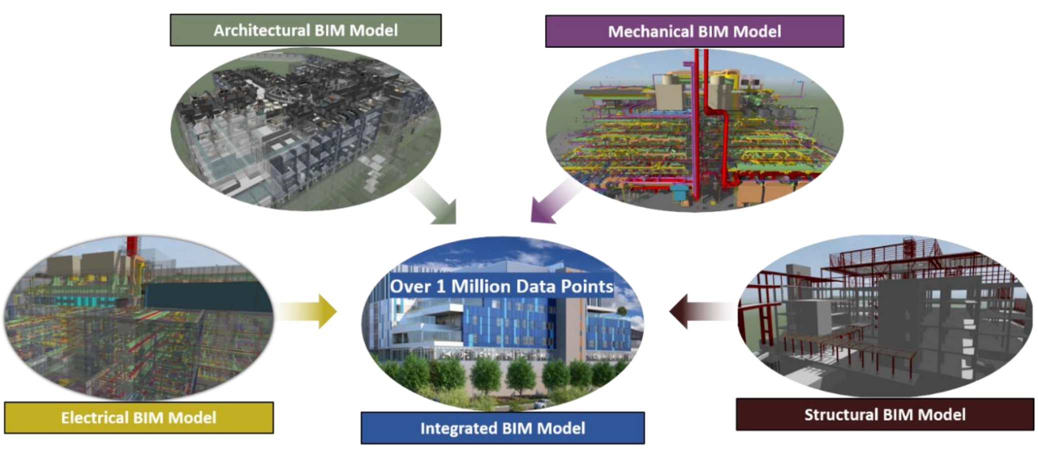



**Figure 2.19: Relevant Design Data in the Integrated BIM to support the Owner's Lifecycle Management Goals**

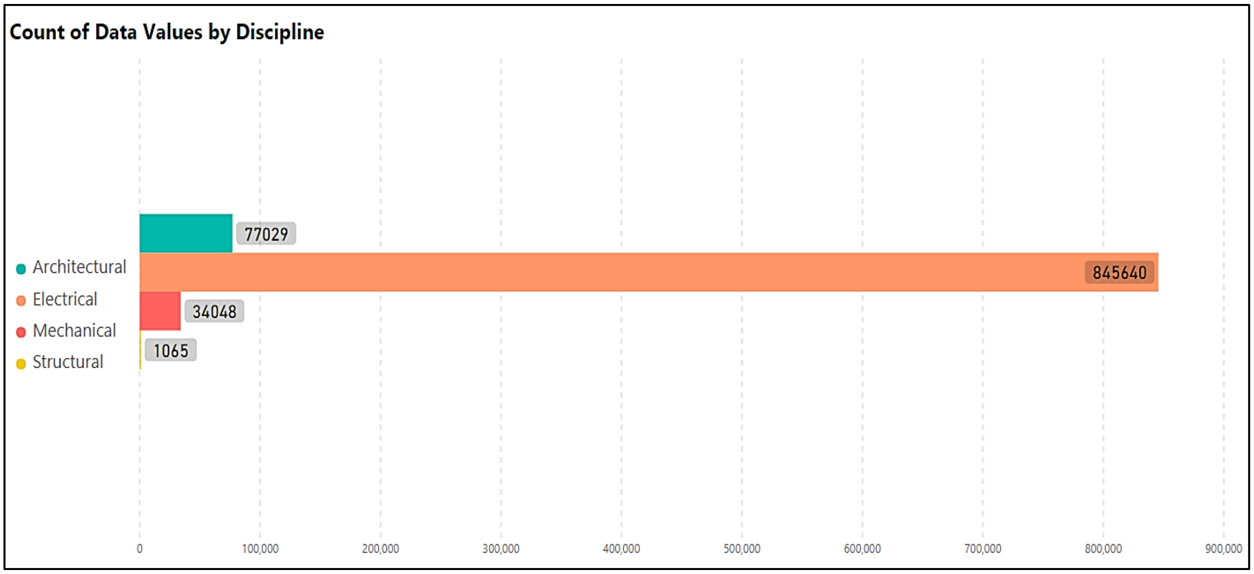



**Figure 2.20: Count of Relevant Design Data in Discipline-specific BIM Models to support the Owner's Lifecycle Management Goals**

## 2.3 Challenge 3: Limited Management Involvement in Design Decision-Making

Despite having a clear understanding of design requirements, issues related to the model health and information quality (discussed above) were witnessed at the end of the design phase. No proactive measures were observed to be taken by the design team to mitigate potential future claims. After widening our analysis lens, we identified the bottleneck to these persistent problems.

Typically, Project Management acts as the face of the organization that joins their forces together in a project. Project Management, in respect to this study, is expected to maintain the lines of communication between all the parties involved, manage expectations for delivery and timeline, and provide support and a gentle push to the teams to fulfill the project requirements. Concerning the compliance with the Owner's BIM requirements (or BIM Compliance), such measures from the project management team were not observed on this project. After having an informal discussion with the design consultant's Project Manager, the Author realized a disconnect between the BIM requirements delivery and overall project delivery.

Due to limited understanding of BIM technology platform, the project management team was not able to quantify the impact of issues and support BIM expert's efforts on mitigating model health issues, maintain high information quality and help manage expectations. The Project Manager showed an earnest desire to invest in a platform which can quickly transform the BIM jargon to a generalized and simple consumable platform. Basically, a simple platform where the project management team can quickly understand the timely progress and pending work in compliance with the Owner's project requirements. During the discussion, the project manager conveyed to the Author that having such platform would help in maintaining "one version of the truth" for the team, thus enabling them to inform decisions to maintain forward progression.

Therefore, the project team's interests to invest in a robust platform that helps teams to understand and manage compliance with the Owner's project requirements and promises to reduce the complexity in managing BIM thus enabling informed decision-making culture, drives the motivation of this research.

# Chapter 3: Research Background

To establish a context of the research, this section provides a background on the key barriers to BIM implementation in the AECO industry and its impacts on compliance with the Owner's BIM requirements and BIM process-related decisions.

Building Information Modeling (BIM) emerged as a promising solution to the AECO Industry's long-sought techniques to "decrease project cost, increase productivity and quality, and reduce project delivery time" (Salman 2011, 241-252). BIM is defined as the modeling of an "essential building design and project information in a digital format, generated through a set of interacting policies, processes and technologies throughout the building's lifecycle" (Succar 2009, 357-375). The building information model contains all the critical piece of geometrical and non-geometrical information required to support the design, procurement, fabrication, construction activities, and operation and maintenance of the facility (Salman 2011, 241-252).

The overall benefits of BIM implementation are widely acknowledged and increasingly well understood to the AECO industry, resulting in significant yet slow growth in BIM adoption over the past decade (Bryde, Broquetas, and Volm 2013a, 971-980; SmartMarket Report 2014; Migilinskas et al. 2013, 767-774; Liu, Issa, and Olbina 2010, 139-145; Gu and London 2010, 988-999; Salman 2011, 241-252; Bryde, Broquetas, and Volm 2013b, 971-980; Azhar, Khalfan, and Maqsood 2015, 15-28). Even though the benefits of implementing BIM on a project are well documented in the literature, studies (summarized in Table 3.1 have identified the following three key barriers to the decelerated global adoption of BIM:

**Table 3.1: Past studies on the major barriers to BIM adoption and its impact on the project delivery**

| ***Barriers to BIM Adoption*** | **Past Studies that Discussed this Barrier** | **Impacts on Project Delivery** |
|---|---|---|
| ***1. BIM and Information Quality (IQ)*** | (Wand and Wang 1996, 86-95; Wang and Strong 1996, 5-33; Y. W. Lee et al. 2002, 133-146; Assaf and Senart 2012, 226-229; Chen and Luo 2014, 64-73; Du, Liu, and Issa 2014, 04014054; Solihin, Eastman, and Lee 2015b, 739-756; Y. Lee, Eastman, and Lee 2015, 176-195; Tuuli Jylhä and Maila 2015, 302-319; Cavka, Staub-French, and Pottinger 2015, 1265-1300; Solihin, Eastman, and Lee 2015a, 739-756; P. Zadeh, Cavka, and Staub-French 2016; P. A. Zadeh et al. 2017, 181-205) | - Potential **Claims** from data Ownership<br>- Affects working **relationships** |
| ***2. Data Complexity and Compliance Assessment*** | (Levitt 2011, 197-210; Bilal et al. 2016, 500-521; Whyte, Stasis, and Lindkvist 2016a, 339-351; Becerik-Gerber Burcin et al. 2012, 431-442; Peng et al. 2017, 483-495; Omar and Nehdi 2016, 143-155; Nepal et al. 2012, 904-923; Yarmohammadi and Castro-Lacouture 2018, 91-111; Demian and Walters 2014, 1153-1165; Fisher 1992; SmartMarket Report 2014; Cavka, Staub-French, and Pottinger 2015, 1265-1300; Cavka, Staub-French, and Poirier 2017, 169-183; Azhar, Khalfan, and Maqsood 2015, 15-28; Bryde, Broquetas, and Volm 2013a, 971-980; Migilinskas et al. 2013, 767-774; Salman 2011, 241-252) | - **Risk** to Project<br>- Affects BIM **Practicability** |
| ***3. Limited Involvement of Higher Management*** | (Penttila 2006, 395-408; Eastman et al. 2008; Liu, Issa, and Olbina 2010, 139-145; Gu and London 2010, 988-999; Salman 2011, 241-252; Liu and Issa 2012; Bryde, Broquetas, and Volm 2013b, 971-980; Migilinskas et al. 2013, 767-774; Bryde, Broquetas, and Volm 2013a, 971-980; Rezgui, Beach, and Rana 2013, 239-258; SmartMarket Report 2014; Smith 2014, 482-492; Azhar, Khalfan, and Maqsood 2015, 15-28; Yarmohammadi and Castro-Lacouture 2018, 91-111; Kyuman, Pollalis, and Pena-Mora Feniosky ; Shaaban, Lockley, and Elkadi 2001, 43-50; Songer, Hays, and North 2004, 173-190; Mao, Zhu, and Ahmad 2007, 242-252; Levitt 2011, 197-210; Hu et al. 2016, 6; Russell, Chiu, and Korde 2009, 1045-1062; Kuo, Tsai, and Kang 2011, 247-262; Chiu | - Uninformed **decisions** by higher management (non-BIM professionals)<br>- Ineffective **Communication**<br>- Lack of skilled personnel |

and Russell 2011, 399-417; Chiu and Russell 2013, 353-373; Chen and Luo 2014, 64-73; Han and Golparvar-Fard 2017, 184-198; Mitropoulos 1999; T. Froese, Han, and Alldritt 2007, 817-829; Aranda-Mena et al. 2009, 419-434; Hartmann and Fischer 2009, 353-365; Davis and Songer 2009, 1324-1333; Rekola, Kojima, and Mäkeläinen 2010; Shen et al. 2010, 196-207; T. M. Froese 2010, 531-538; Jung and Joo 2011, 126-133; Arayici et al. 2011, 189-195; Ho and others 2012; Paul and Javernick-Will Amy 2013, 510-518; Li et al. 2017, 195-206)

## 3.1 BIM and Information Quality (IQ)

Assessment of the BIM model and information quality is essential to efficiently evaluate the project performance and compliance with building Owner's requirements (P. A. Zadeh et al. 2017, 181-205). Studies have identified that the lack of information quality (IQ) is one of the major barrier to BIM implementation (Du, Liu, and Issa 2014, 04014054; Y. W. Lee et al. 2002, 133-146; Solihin, Eastman, and Lee 2015a, 739-756; Tribelsky and Sacks 2010, 189-206; P. A. Zadeh et al. 2017, 181-205). Poor IQ directly affects the project scope, the Owner's building lifecycle management goals and the stakeholders involved can likely miss a crucial opportunity to make their services more valuable to the Owners and differentiate themselves from competitors as BIM use becomes increasingly prevalent (SmartMarket Report 2015, 60). Unsatisfactory IQ results in "ineffective project management, uncertain process results and time loss or cost increases in maintenance processes" (Volk, Stengel, and Schultmann 2014, 109-127).

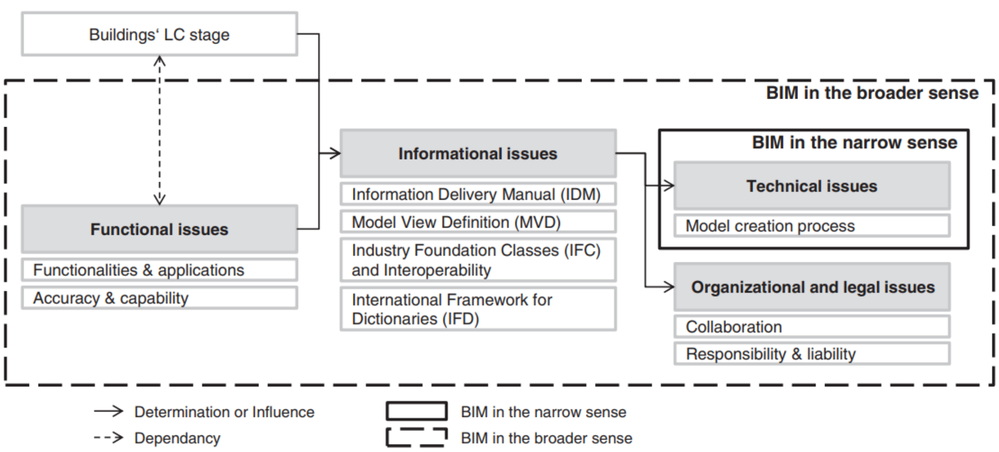



**Figure 3.1: Relations between functional, information, technical and organizational issues of BIM (Source: (Volk, Stengel, and Schultmann 2014, 109-127))**

Any interaction with the BIM model can be a source of the IQ issue (P. A. Zadeh et al. 2017, 181-205). “Two types of expert software might interact with a BIM model: (1) **data input** applications providing services of import, data capture and monitoring, data processing or transformation of captured data into BIM or (2) **data output** applications providing reports or technical analyses or clash detections” (Volk, Stengel, and Schultmann 2014, 109-127). Hence, informational issues can be a resultant of “data input” from either (1) Technical issues during the BIM model creation process, or (2) Organizational issues like ineffective communication, collaboration, and decisions (Volk, Stengel, and Schultmann 2014, 109-127). The “data input” and “data output” phases are carried out recurrently throughout the project delivery process, i.e., from design development to the handover of the project. Therefore, it is important for all the stakeholders to monitor IQ throughout the project development, to ensure conformance to the building Owner’s BIM requirements. (P. A. Zadeh et al. 2017, 181-205). Also, “to prevent unwanted project outcomes from occurring, the modeling process needs to be effectively managed. This effective management requires an ability to monitor the modeling process closely and correctly measure the modelers' performance” (Yarmohammadi and Castro-Lacouture 2018, 91-111).

(P. A. Zadeh et al. 2017, 181-205) has made the most recent contribution to this area of study by recognizing the fundamental research related to IQ in computer science and mapping it to the AECO domain. Per their analysis, the Owner’s expectations with the delivered information can be categorized within the following IQ dimensions (P. A. Zadeh et al. 2017, 181-205):

1. Information Completeness,
2. Information Accuracy (Correctness and preciseness),

3. Information Understandability,
4. Information Unambiguity,
5. Information Well-formedness.

Variety of tools have been developed that can be used to assess IQ of BIM models and hence, the compliance with project's BIM requirements. Basic data analysis can be performed using the "Schedules" feature of BIM authoring tool like Autodesk Revit. BIM-based construction management tools such as Autodesk Navisworks allows BIM professionals to run simple clash detection queries. In addition, intelligent software platforms such as Solibiri Model Checker (SMC), iTwo, and Autodesk Model Checker are available to create and run complicated queries and extract required information from BIM models to assess the compliance (Solihin, Eastman, and Lee 2015a, 739-756; P. A. Zadeh et al. 2017, 181-205). BIM specialists or professionals are needed to create complicated queries on such platforms and the compliance reports generated can be very overwhelming for the higher management to inform decisions. It has also been observed that the Owners are reluctant at implementing BIM in a broader spectrum of operations and maintenance because of the difficulties in assessing the IQ. "One can't ask for something that one can't assess" and one can't provide something of high quality if one can't assure and control (P. A. Zadeh et al. 2017, 181-205).

## 3.2 Data Complexity and Compliance Assessment

Large volumes of relevant geometrical and non-geometrical data needed to support different phases of building's lifecycle is exponentially growing in BIM-based project delivery (Bilal et al. 2016, 500-521). This data needs to be digitally managed by the professionals from the design to the maintenance of the building (Whyte, Stasis, and Lindkvist 2016b, 339-351; Bilal et al. 2016, 500-521).

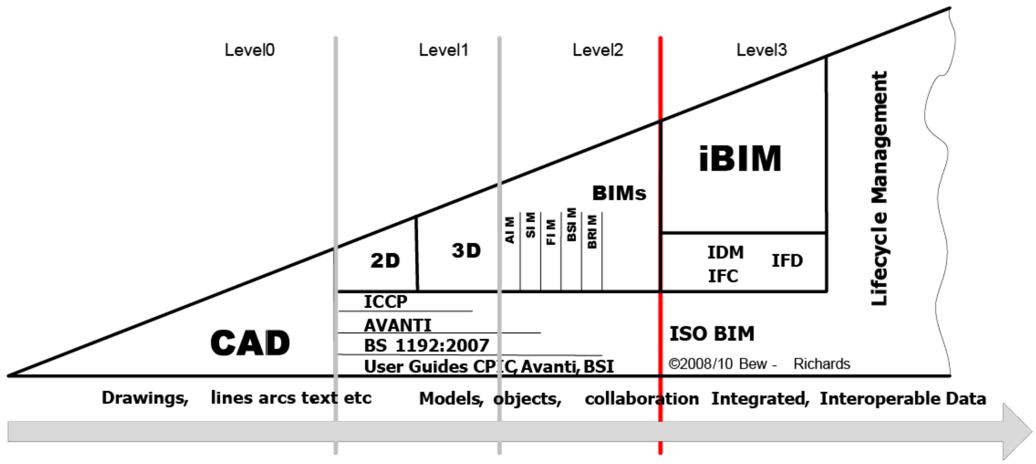



**Figure 3.2: BIM Maturity Model (Source: [www.level2bim.org](http://www.level2bim.org))**

Creating or integrating digital information of a building or any other facility using BIM is trending upwards over time. Bew-Richards BIM Maturity Model (shown above in Figure 3.2) is a testament to the rising digital data generation and management over different maturity levels, i.e., from 0 to 3. Explanation of each maturity level is out of the scope of this research and can be retrieved from www.level2bim.org/ or www.bimtaskgroup.org. It would be safe to assume that the mismanagement of information in digitally-enabled projects can have significant consequences on the overall project information delivery. Hence, efficient delivery of a coordinated graphical and non-graphical project information model requires skills to manage such information and harness insights from data to drive decisions related to BIM performance and compliance.

"The phenomenon to process copious amounts of data and to extract useful insights from the data to inform decisions – labeled as Big Data – represents a new paradigm within the AECO

Industry" (Bilal et al. 2016, 500-521). Past researches imply that "large volumes of heterogeneous data" is generated in the BIM environment and the principles of Big Data are not embraced by the industry (Bilal et al. 2016, 500-521). This inability to extract insightful business values from large volumes of the BIM data has resulted in an information management problem, resulting in uninformed and inefficient project delivery. Research shows that the challenge of managing 'I' of BIM is not new to the industry. (Volk, Stengel, and Schultmann 2014, 109-127) discussed that fewer papers deal with aspects of data management and few past researches discussed this challenge and its impacts. (Gu and London 2010, 988-999) mentioned that digital data management and organization is critical to facilitate BIM adoption in the AEC industry. (Salman 2011, 241-252) claimed that the poor quality of the data inputted to the BIM model "entails a great deal of risk" to a project. (Jung and Joo 2011, 126-133) discussed the issue of invariability in the quality of BIM data to affect the BIM practicability in construction business functions. (Volk, Stengel, and Schultmann 2014, 109-127) discussed the key challenge to BIM implementation is (1) "handling uncertain data in BIM", and (2) "updating information in BIM".

Structuring of data within the BIM environment is very critical to effectively evaluate the project performance and compliance with the Owner's BIM requirements. The introduction of international COBie standard, OmniClass system, and Uniformat system can help store the building's information in BIM in a structured way (Volk, Stengel, and Schultmann 2014, 109-127). Thus, the data cleaning or parsing efforts required to structure the data to evaluate the performance and compliance effectively is significantly lower than the information generated outside the BIM environment.

To achieve accessibility and flexibility with parametric BIM data, the Application Program Interface (API) of the BIM authoring tool needs to be tapped (Shahrokhi 2016). “In computer programming, an application programming interface (API) is a set of subroutine definitions, protocols, and tools for building application software” (Wikipedia contributors 2018). In general terms, API is a method of communicating with the software. Typically, computer programmers use text-based scripting to access the information using API, but it can be difficult for an average BIM user to access this information using computer programming (Autodesk 2017). Visual Programming Language (VPL) can help an average BIM user to access such information outside of the constraints of the software interface without any programming or coding experience (Autodesk 2017). Tools like Autodesk Dynamo or Grasshopper have been developed to democratize BIM data through an approachable graphical algorithm editor, as shown in Figure 3.3below. By using such tools, tedious parametric data workflows in BIM can be streamlined (Autodesk 2017).

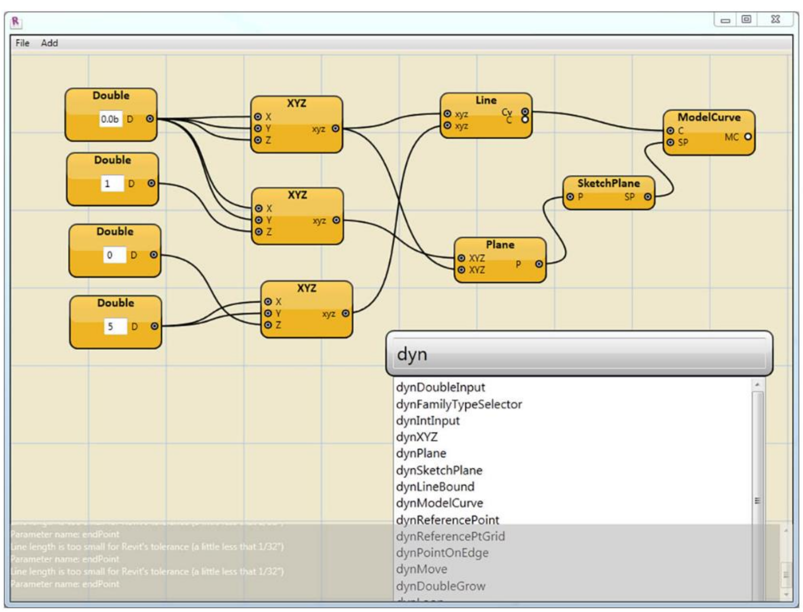



**Figure 3.3: Interface of Visual Programming Language Platform (Source: Autodesk Dynamo Primer, 2017)**

## 3.3 Limited Involvement of Higher Management

The Associated General Contractors of America (AGC) perceived Building information model as “a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which relevant data can be extracted and analyzed to generate information to make decisions and improve the process of delivering the facility” (AGC, 2005). Despite fast developments and spreading standards, challenging opportunities arise in informing decisions from the information generated in BIM environment (Volk, Stengel, and Schultmann 2014, 109-127). One such reason is ineffective collaboration and communication due to the learning curve and training time required to get proficient with BIM technologies (Bilal et al. 2016, 500-521).

As per (SmartMarket Report 2014) research, BIM adoption in a broader spectrum for the facility maintenance and operations purposes is slower because the Owner organizations have difficulty in utilizing the BIM technologies for assessing the BIM quality. Consequently, in many projects, the Owners do not include valuable FM information needs in the contracts and project requirements (SmartMarket Report 2014). Next year, SmartMarket study (2015, 60) reported that almost 74% of the Building Owners believe that the use of BIM models and data provides them tangible value, out of which 80% of the building Owners benefit from the use of BIM data to drive their facility’s operations and maintenance. Despite understanding the benefits of BIM, it is not utilized at its full potential because of the complexity and learning associated with the technology.

Studies show that the project performance and compliance are related to the learning curve of BIM technologies. (Volk, Stengel, and Schultmann 2014, 109-127) mentioned that even though BIM is spreading in AEC industries worldwide, the “need for qualified personnel” and “alignment of training content” remains a bottleneck of BIM implementation in new buildings. (Salman 2011, 241-252) claimed that the parties involved in the project delivery must identify a way to reduce the learning curve of BIM to optimize the BIM performance. (Ku and Taiebat 2011, 175-197) surveyed about 30 contracting firms in the US and found the learning curve and lack of skilled personnel results in low project performance, which in turn is a major barrier to BIM implementation. (T. Froese, Han, and Alldritt 2007, 817-829) conducted an industrial survey on the Canadian construction IT industry and identified that the limited proficiency in the BIM technologies greatly affects the collaboration, including “communications, document management, and interoperability”. The study considered this to be the most important “opportunity for improvement to the Canadian construction industry”. (Arayici et al. 2009, 1342-1351) study mentioned that “the lack of skilled personnel and the learning curve of new tools” is a most commonly observed barrier to BIM implementation. Thus, it can be concluded that the learning curve of BIM technologies affects the collaboration and communications, further leading to uninformed decisions (T. Froese, Han, and Alldritt 2007, 817-829; Aranda-Mena et al. 2009, 419-434; Davis and Songer 2009, 1324-1333; Rekola, Kojima, and Mäkeläinen 2010; Gu and London 2010, 988-999; T. M. Froese 2010, 531-538; Jung and Joo 2011, 126-133; Becerik-Gerber, Gerber, and Ku 2011, 411-432; Li et al. 2017, 195-206).

(Azhar, Khalfan, and Maqsood 2015, 15-28) claimed that “the foundations of BIM are laid on two pillars: communication and collaboration”. Greater collaboration and communication needs an intelligent and an integrated model which facilitates BIM adoption through “informed selection of tools based upon project collaborators’ readiness, tool capabilities and workflow dependencies and cognizant of the potential to integrate and collaborate across all phases of the project lifecycle” (Gu and London 2010, 988-999). (Migilinskas et al. 2013, 767-774) claimed that BIM implementation requires the urgent development of the intelligent tools that enable “efficient and direct coordination and monitoring processes between project participants and team members to inform project-level decisions”. (Migilinskas et al. 2013, 767-774) associated “Intelligence” as “information associated with graphics”. (Chen and Luo 2014, 64-73) harnessed the power of visualization to help project participants understand the quality progress and collaborate more effectively for construction project management. (Bryde, Broquetas, and Volm 2013a, 971-980) mentioned that improved collaboration between project managers and other stakeholders reduces the time needed for documentation of the project and, produces beneficial project outcomes.

In new buildings, collaboration through BIM is increasing, especially due to improving capacities of communication (Volk, Stengel, and Schultmann 2014, 109-127) but these platforms lack functionality in providing deep, granular, and real-time insights about the project performance or compliance with the Owner’s BIM requirements. (Yarmohammadi and Castro-Lacouture 2018, 91-111) mentioned that the real-time monitoring of design development events could enable managers to detect and prevent poor modeling practices, affecting the compliance with requirements. New digitally enabled approaches to improve collaboration and communication are emerging in the construction industry. As the information generation in the industry ramps up, visualization or visual analytics of large digital datasets can provide the basis for more “responsive, flexible and real-time decision-making in project delivery” (Lindkvist, Stasis, and Whyte 2013, 173-176; Levitt 2011, 197-210). BIM data can be used for developing an advanced, real-time, visualization project dashboards, allowing project managers to track issues and determine the participants affected by the problem at hand (Yarmohammadi and Castro-Lacouture 2018, 91-111). "A multilayered visualization platform can support design managers to quickly and easily identify design issues, analyze the causes of these design problems, and communicate the problem to the design team at the selected level of detail" (Yarmohammadi and Castro-Lacouture 2018, 91-111).

"BIM is not a software solution; it is a process underpinned by technology and collaboration"[3]. For effective BIM execution, it is critical for project participants to have a strong grip on both the technology and collaboration. No matter how extensively the BIM tools are utilized, if there isn't proper collaboration – or vice versa – project outcomes are likely to be unsatisfactory. "BIM is a collaborative approach to working, which requires multi-party input and integrated accurate data sharing, where project decisions are inherently made in the interests of the project"[2].

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[2] BIM Implementation – HOK BuildingSMART by David Light. Published on 01 October 2011. Retrieved from webpage on 05 June 2018. URL - https://www.thenbs.com/knowledge/bim-implementation-hok-buildingsmart

# Chapter 4: Interactive Visual Analytics for BIM Compliance Assessment and Design Decision-Making through Action-Research

In this Chapter, we present the methodology used to achieve the three objectives of this research.

Before diving deeper into the methodology, it is important for the reader to understand the phases of compliance with the BIM requirements or ‘phases of BIM compliance’. The process of attaining compliance with the BIM requirements is divided into two phases: (1) Data Integration and (2) Data Extraction.

- **Phase 1:** Data Integration involves integrating the accurate data to a BIM model in good health.
- **Phase 2:** Extract the integrated data, parse and check the quality of the BIM data to ensure compliance with BIM requirements on the project.

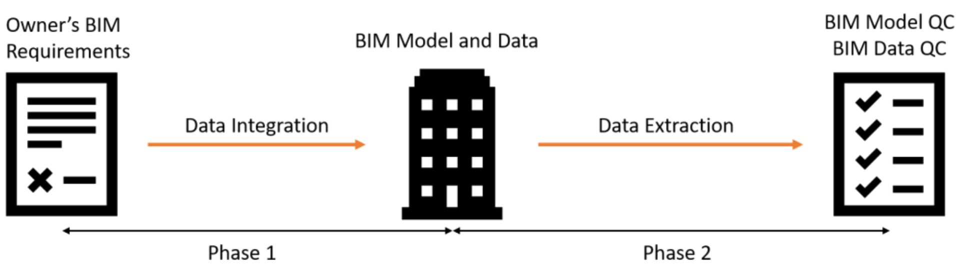



**Figure 4.1: Phases of BIM Compliance during the Design Phase**

As observed by the Author and discussed in the case study section of this thesis, the existing practices employed by industry are not very efficient and the end product has various quality issues. The first two objectives of this research are formulated to improve these two phases of BIM compliance and the third objective aims to improve the team’s understanding of compliance through effective data visualization and to promote data-driven decision-making. The first objective of this research aims to optimize the data integration phase (Phase 1), and the lessons learned from the first AR cycle informs the second and third objectives. The second and third objectives (phase 2) of the research is to automate the process of relevant data extraction and to parse this information for effective information management.

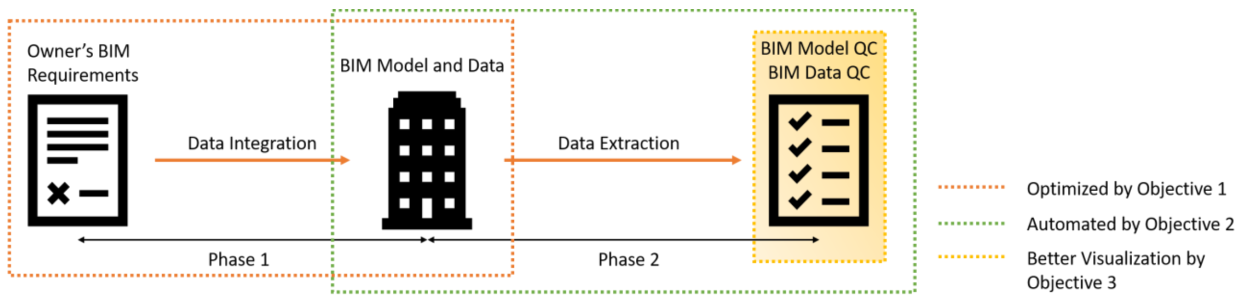



**Figure 4.2: Research objectives integrated with the phases of BIM compliance**

## 4.1 Action Research Cycle 1: Technology-Driven BIM Compliance Workflow for Qualitative Data Integration to BIM Models

Action Research was used to create a technology-driven workflow for BIM data management to assure compliance with the Owner's BIM requirements. Figure 4.3 depicts the research methodology or the AR cycle used on the case study (described in Chapter 2). The Author and the project's design team performed the first action-research cycle over a 7-month period, during the duration of this study from June 2017 to December 2018. The following research activities were carried out in this AR cycle:

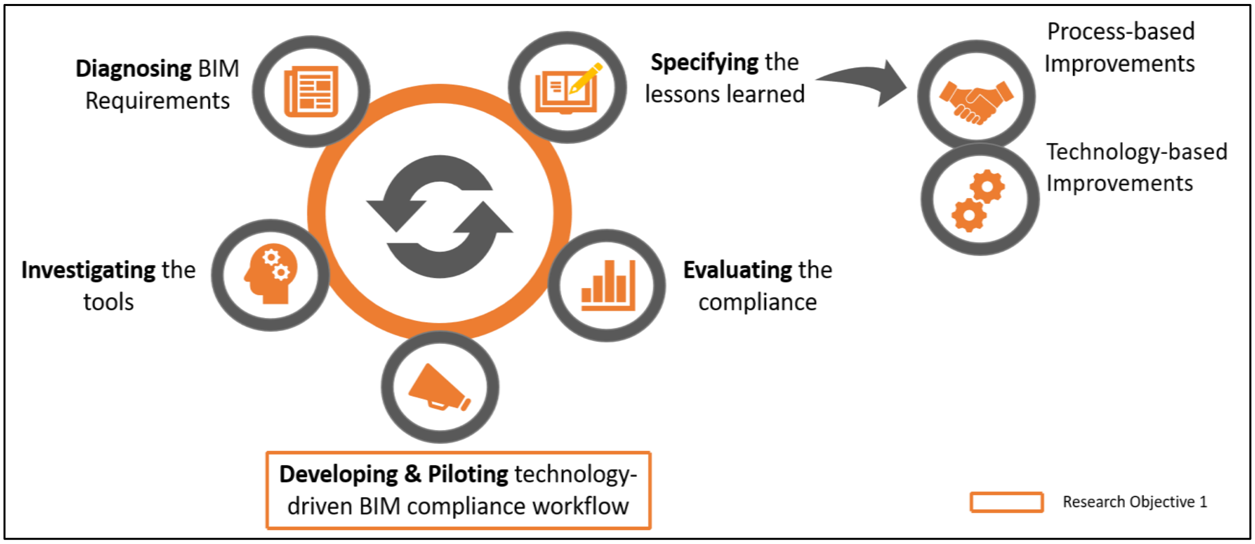



**Figure 4.3: Action research cycle 1 to address the first research objective (7 months)**

### 4.1.1 Diagnosing the BIM Requirements

The first step was to diagnose the current practices, project documents and identify the problem that will likely affect the compliance with the Owner's BIM requirements on this project. To understand the BIM requirements, all the project documents related to the Project's BIM requirements were thoroughly analyzed.

As defined in the project's BIM standards, the Owner's overall BIM goal on this project is to *"utilize a BIM process to derive consistent digital data that can be used to drive downstream uses during the entire life cycle of the facility, from design, through construction and on into Facility Maintenance and Operations"*.

The following documents were identified and reviewed:

#### 4.1.1.1 BIM Standards Requirements (BSR)

This document provided details of the BIM requirements and the guiding principles that the project team was required to follow to be compliant and support Owner's BIM goals.

#### 4.1.1.2 BIM Project Execution Plan (BEP)

BEP documented the 'BIM process' requirements in detail, which involved inputs from the project team to define responsibilities and expectations by all the participants. Within this document, the 'BIM process' referred to the process of utilizing and sharing of structured data, following agreed processes and protocols, to generate a digital prototype that can be tested for form, fit and function prior to construction. The objective is to provide a valuable data set for use throughout the entire lifecycle of the facility.

The project team agreed to the following:

- Validation – One version of data (hence, truth) for all,
- Visualization – Clear understanding and better communication among all,
- Data Access – Structuring of data for point and click access.

As discussed in the case study section of this research, it is significant that the design team deviated from these agreed terms.

#### 4.1.1.3 BIM Design Data and Geometry Specifications (DGS)

This document predefined the minimum data requirements for objects on a per Revit category basis. Design consultants were responsible for incorporating these data requirements in the BIM models at high quality. The design team was also required to provide the time when that information will be completely available in the BIM models.

FMO requirements were also specified, in terms of 'shared parameters'. During the design phase, the FM requirements focused on having a clear 'object list' and object list relationship matrix. These requirements were added to the data and geometry requirements. This object list was to be used by the Owner to track objects throughout the entire lifecycle of the facility. Figure 4.4 is provided below as an example to the show the BIM data requirements for 3D objects.

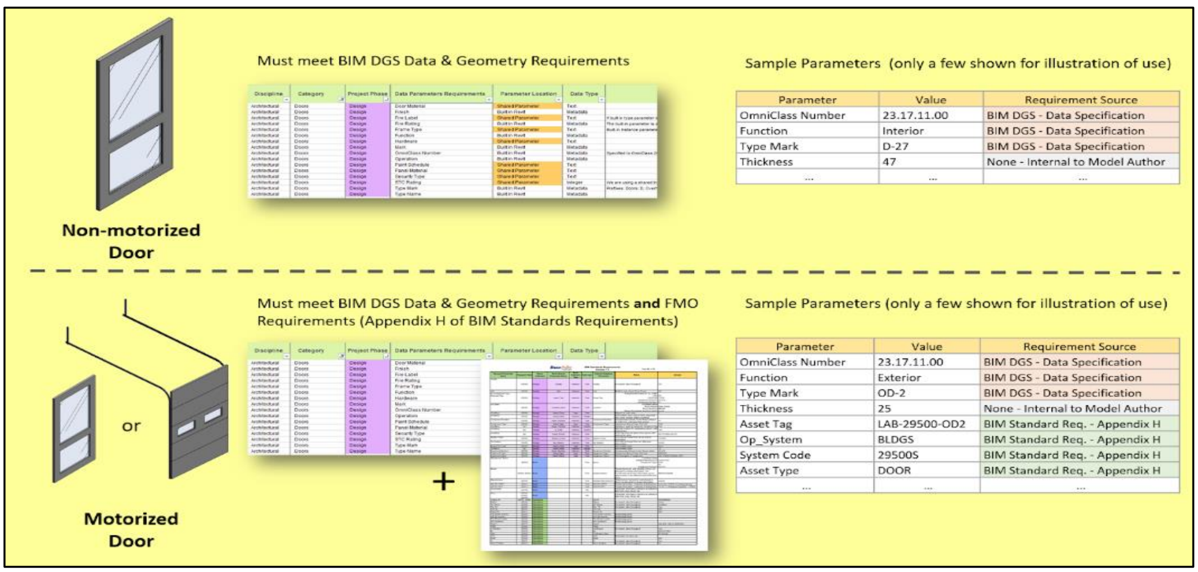



**Figure 4.4: Sample design and FMO parameter requirements**

### 4.1.2 Investigating the BIM Compliance Assessment Tools

At the end of 'diagnosing' phase, the Author extracted the following critical set of the Owner's BIM requirements, specifically pertaining to the BIM model and data requirements:

1. **BIM Model Health Requirements**

    - BIM model should be in good health, and the health standards were defined in the BSR. Basically, the models should have low impactful warnings, views only on sheets, only system and component families, etc.
    - Element's family and type name should be descriptive and not include "standard", "generic", "default", etc.
    - Elements should be defined in the correct categories. For example, "Doors" should not be defined under "Walls".

2. **BIM Data Requirements**

    - A list of the 426 data parametric requirements was identified that were contractually required by the Owner during the design phase to support overall BIM goals. These data requirements should be integrated and populated in the models.
    - Include OmniClass and Uniformat Classification system to the component and system families was marked critical to help the Owner structure the digital data.
    - Data values (text, metadata, integer, etc.) should be integrated accurately as defined in the DGS document.

Failure to abide by any of the above requirements would result in non-compliance, likely affecting the Owner's overall BIM goals and resulting in legal complications. Since the design phase is a very dynamic process, and continuous updates and omissions are made throughout this process – a more automated, rule-based platform was deemed pivotal to check the BIM models and integrate data. Hence, the Author began investigating various tools available to fulfill overall BIM needs on the project:

**Table 4.1: Tool requirements specific to the Owner's BIM requirements (TBI = To be investigated).**

| Tool Requirements | Tool Type | Software Name |
|---|---|---|
| Check the model's health and data completeness | TBI | TBI |
| Integrate OmniClass and Uniformat Classification system data to 3D elements | TBI | TBI |
| Data analysis to evaluate the data value quality and manipulate the values quickly | TBI | TBI |

After investigating for nearly two months, the following tools were identified to satisfy the qualitative data integration to BIM models and BIM quality assessment needs.

#### 4.1.2.1 BIM-based Model Checking tools

BIM-based model checking tools authored by Autodesk, Model Checker and Model Checker Configurator, were investigated to automatically check BIM models and data based on a set of the Owner's BIM requirements. Several pre-built check-sets were already included in this tool but considering a custom set of requirements on this project, the Author semantically configured about 500 unique checks for each discipline's BIM model. Each configuration (sample is shown in Figure 4.5) was created to check various BIM model health parameters and information completeness parameters.

The model check configurator uses a regular expression or "regex", which can be used to create a customized text string or a sequence of characters to define the search patterns. This greatly helps in filtering the customized categories, elements or model checks. It also uses a BIM database exploration tool to "view and navigate element properties and relationships" which gave the Author an ability to interrogate the API behind BIM authoring tool, Autodesk Revit, and the 3D elements designed within. This allowed the Author to access and evaluate the BIM model information in a simple programmatic way.


**Figure 4.5: Model checker configuration and compliance report for the architectural model**

The model check configuration can be run directly in the BIM authoring tool thus enabling project teams to evaluate their compliance at any given time. After uploading and running in the BIM authoring tool, each configuration evaluates the model for the custom set of BIM requirements and generates a compliance report in less than 5 minutes. The compliance report is generated in a PASS/FAIL format. If any element meets the criteria defined in the model check configuration in compliance with the Owner's BIM requirements is automatically flagged as PASS, otherwise FAIL. The report is directly integrated with the model and hence, enables the user to fix non-compliant elements in real-time.

#### 4.1.2.2 BIM-based Data Classification and Organization tool

As documented by the Owner, classification management was critical to categorize and classify the built environment. BIM-based data classification and organization tool authored by Autodesk, Classification Codes Manager, was used to satisfy the Owner's BIM requirements, specifically assigning OmniClass Number (system table 23) to the component families and Uniformat Code to system families. OmniClass was used for organization and easy retrieval of product information for all 3D objects in the built environment to support all phases in the project lifecycle. Uniformat was used to arrange construction information and organize functional elements, specifically used for quantity and cost estimation.

This tool has a robust database of several major classification systems and can be used to quickly assign multiple classification systems to multiple 3D elements at once. The classification system database is referenced from a fully customizable Microsoft Excel file. Integration of this information helps in structuring and organizing project's information. This classification structure can then be pushed into the Owner's Computerized Maintenance Management System (CMMS), sometimes also referred as Enterprise Asset Management (EAM), for organizing asset information during FMO and cost estimation. In brief, this tool can also be used to streamline interoperability of information across various tools. Figure 4.6 is provided to show the easy and interpretable user interface of this tool.

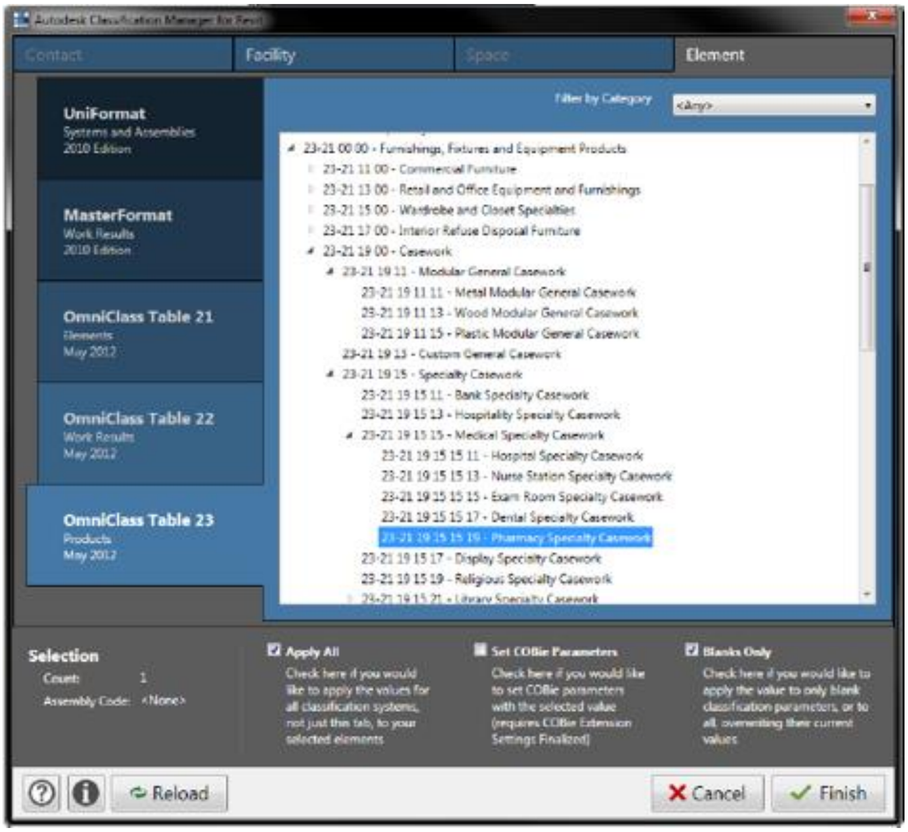



**Figure 4.6: Autodesk's classification codes manager for organizing asset information**

### 4.1.2.3 BIM Data Management tool

After reviewing the ambitious BIM requirements, the project team had an understanding that vast amounts of data will be generated to support the Owner's lifecycle management goals. Since the Owner had a desire to leverage the generated information for downstream purposes, a critical requirement was to assure a high quality of information – thus to avoid the errors and wasted time from double-handling of the data. It was observed that the BIM authoring tool used during the design phase lacks the simplicity and flexibility to review and manipulate vast amounts of data at once. Limitation in such feature leads to redundant data entry in the BIM authoring tool. Moreover, the architects, engineers and project management team who were not proficient with

BIM technologies faced difficulties in accessing and visualizing the information to assess the quality and mitigate any legal issues resulting out of information inaccuracy.

A tool that promotes effective BIM information management, Ideate BIMLink, was identified to mitigate such issues and inefficiencies from happening during the design stage. This tool enabled the users to quickly access, evaluate and update important BIM data dramatically reducing time spent on such tasks. It offered simple interface and ease of use to all the users, irrespective of whether they are BIM technology capable or not. Volumes of information can be pushed out of the BIM authoring tool to Microsoft Excel in minutes for analysis and updates, and the manipulated and validated BIM information can be pulled back into the BIM model with ease, accuracy, and speed. Figure 4.7 and Figure 4.8 are provided to represent the process of exporting and importing of information from BIM models.

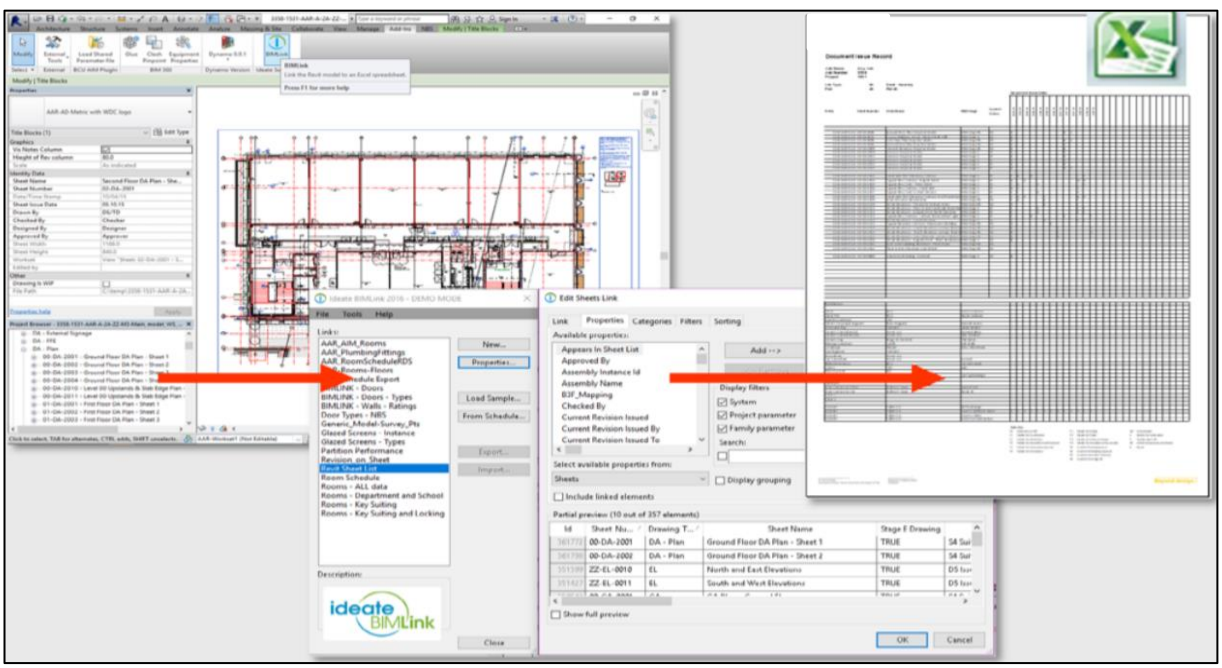



**Figure 4.7: Process for exporting BIM information from Revit to Microsoft Excel for quick reviews and updates (Source: Ideate BIMLink)**

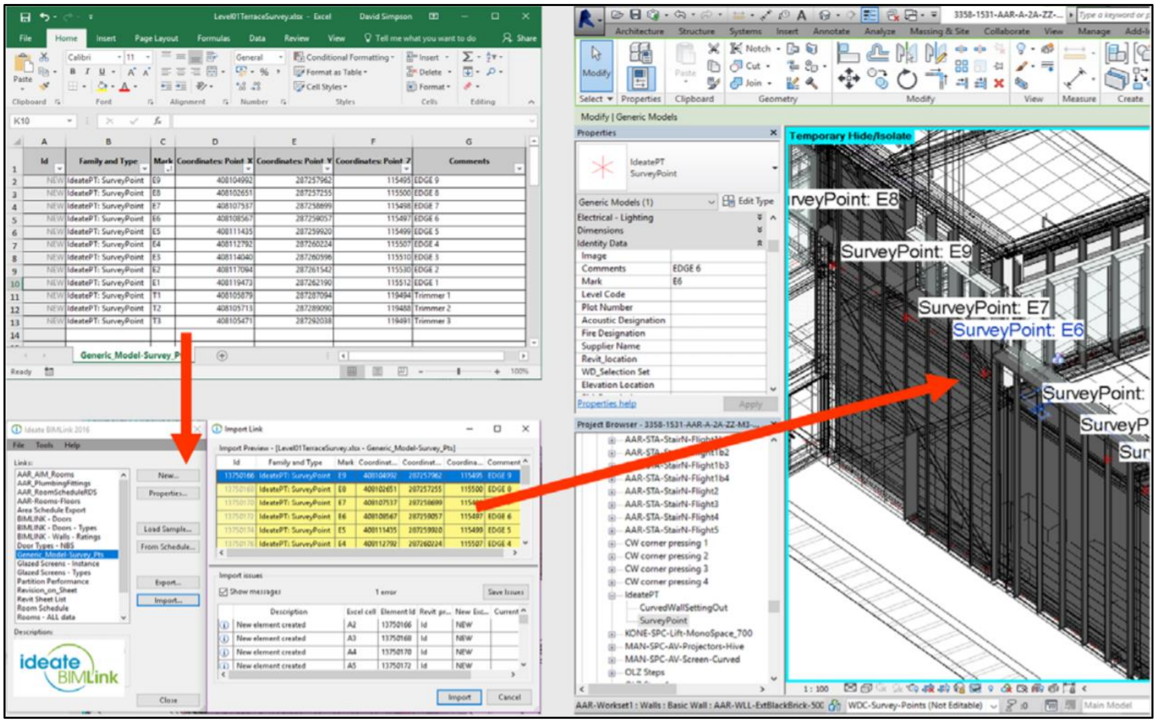



**Figure 4.8: Process for importing updated and validated BIM information into the BIM model (Source: Ideate BIMLink)**

Hence, after exploration and investigation of about two months, the tools required to enable users to satisfy the Owner's BIM requirements were identified as follows:

**Table 4.2: Tools identified to streamline BIM compliance workflow during the design phase**

| Tool Requirements | Tool Type | Software Name |
| --- | --- | --- |
| Check the model's health and data completeness | BIM-based Model Checker | Autodesk's Model Checker and Model Checker Configurator |

| | | |
|---|---|---|
| Integrate OmniClass and Uniformat Classification system data to 3D elements | BIM Data Classifier and Organizer | Autodesk's Classification Codes Manager |
| Data analysis to evaluate the data value quality and manipulate the values quickly | BIM Data Management | Ideate BIMLink |

### 4.1.3 Developing and Piloting Technology-driven BIM Compliance Workflow

Once the tools were investigated and customized configurations were created in compliance with the Owner's BIM requirements, the next phase in the AR cycle was to take action with the planned tools. It is known that the tools can every equate to success on their own however integration of the tools in the pragmatically developed process can lead to desired results. To take action, the tools/technologies had to be embedded in a compliance workflow. This would result in a technology-enabled compliance workflow where the team's responsibilities and the tools required to effectively and efficiently fulfill their responsibilities were in-place and standardized for the design phase.

The Author conducted frequent meetings with the BIM Manager on the project to get in-depth information about the existing compliance workflow. The BIM Manager conveyed to the Author that a workflow is yet to be developed and at the start of the design phase, compliance with the Owner's BIM requirements was not formally pursued. Hence, the BIM Manager's earnest desire to create a technology-enabled workflow to ensure compliance and mitigate the Owner's concerns during the model audits resulted in an interest alignment with this research.

After weeks of pragmatic discussions, the Author and the BIM Manager created the workflow as shown in Figure 4.9 below.

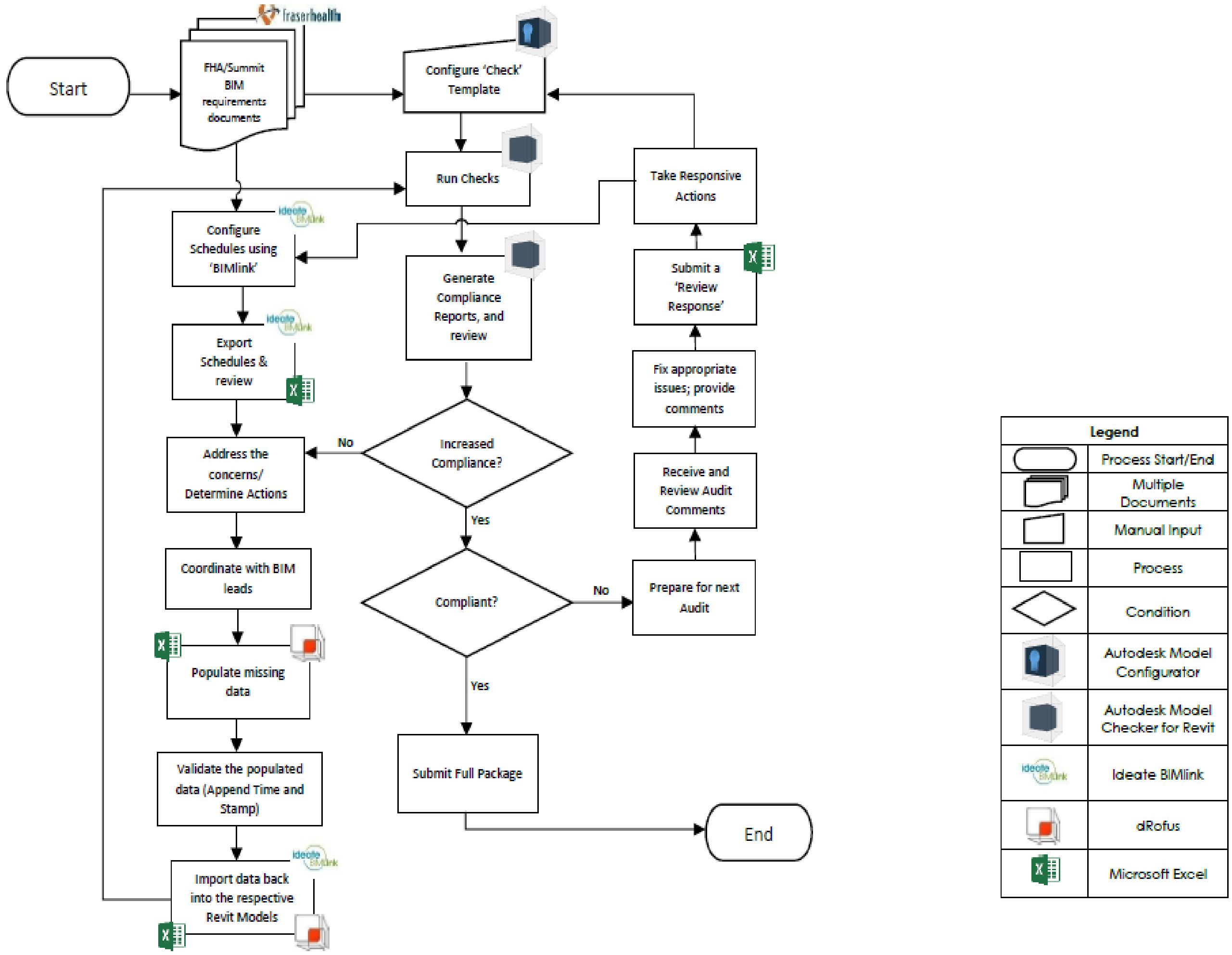



**Figure 4.9: Technology-enabled BIM Compliance Process**

The workflow, shown in Figure 4.9, was further divided by the players in the process, namely the design team, the BIM team, and project management team. The Project Management team would act as the face of the design organization to the Owner and responsible for smooth and timely submissions of the deliverables to the Owner for audit. As seen in Figure 4.10 below, categorization was done to help teams understand their responsibilities in this compliance process. As it can be inferred from the figure below, the design team is liable for the activities that involves integrating the team's technical contributions to the BIM models; the BIM team is responsible for ensuring the compliance by running BIM-based checks. The project management team is responsible for submissions. Overall, the design team deals with the most critical activities and data-intensive technologies for swiftly integrating data to the BIM models for achieving compliance with the Owner's requirements.

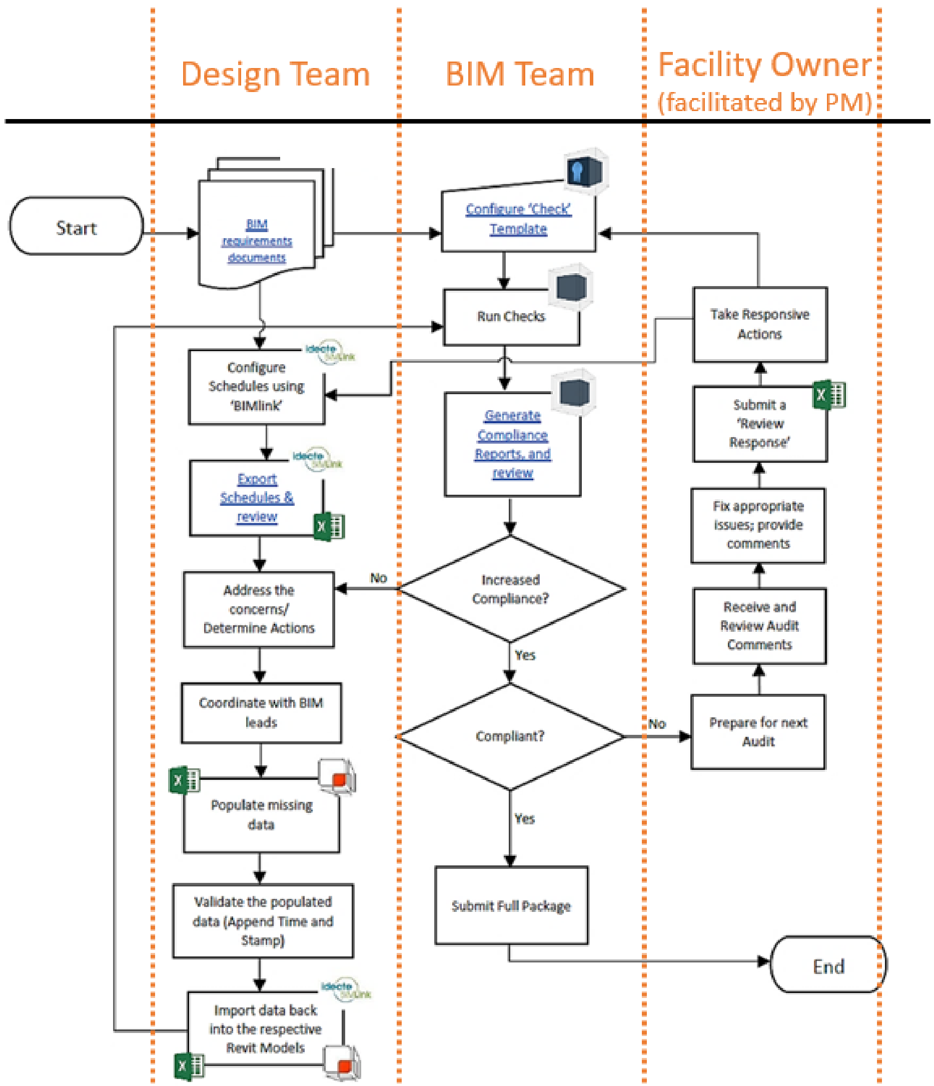



**Figure 4.10: BIM Compliance Process, categorized by team's responsibilities**

Once the process was defined, the BIM Manager called a ‘compliance kick-off’ meeting with the entire design team involved in the project. The team was familiarised with the entire BIM compliance process and the technologies involved to streamline the process. The current status of compliance with the Owner’s BIM requirements was retrieved from the model check reports for each discipline. The Compliance reports with existing status were presented to the entire team. The process to achieve 100% compliance at the end of design phase was discussed in detail. The responsibilities of each team were discussed in the meeting, as shown in Figure 4.11 below.

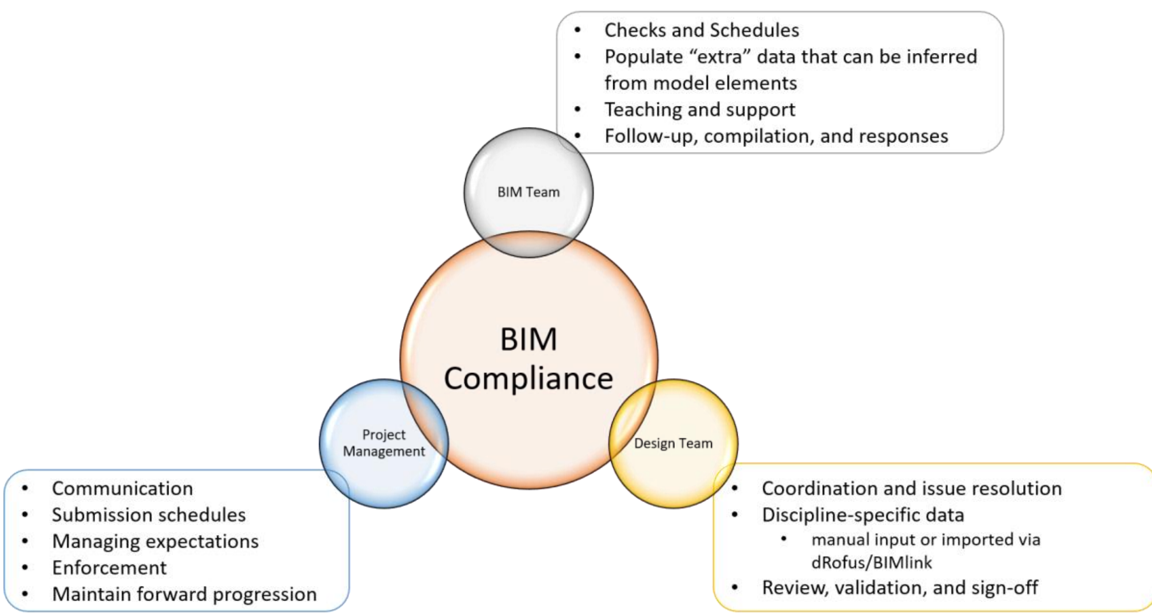



**Figure 4.11: Roles and responsibilities of the design team in BIM compliance process**

### 4.1.4 Evaluating BIM Compliance over time

Once the team was familiarized with the tools involved and the technology-enabled process was kicked-off by the BIM manager, the next step and the core responsibility of the BIM team was to evaluate or assess the trends of compliance with the Owner’s BIM requirements over time. These trends were documented for learning purposes. The research team and the BIM manager had an understanding that the industry is changing, and this is an excellent opportunity to get comfortable with the increased BIM requirements that will soon be a standard on more projects. The Author evaluated the compliance trends bi-weekly through the following procedures: (1) Bi-weekly BIM-based Model health checks using BIM model checker, (2) Bi-weekly BIM-based data compliance checks using BIM model checker, and (3) Bi-weekly meetings with the discipline to facilitate teaching and support.

The model health and data trends were recorded manually from the model checker's compliance reports to a Microsoft Excel sheet. Figure 4.12, Figure 4.13 and Figure 4.14 below are the snapshots of the excel file. The research team used these trends for learning purpose, and the learnings are presented in the last chapter of this thesis. These trends were also presented to the design team during the bi-weekly meetings to help them understand their progress over time. In the case where no progress was observed, the justification and comments from the design team were recorded and conveyed to the Owner through BIM execution plan.

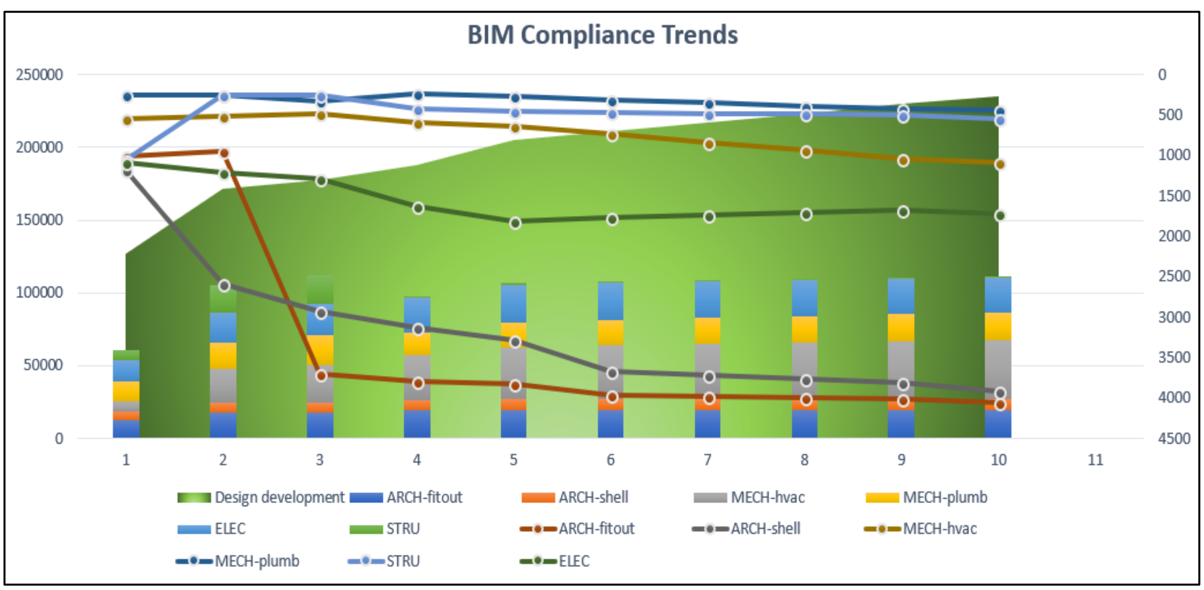



**Figure 4.12: Overall BIM compliance trends**

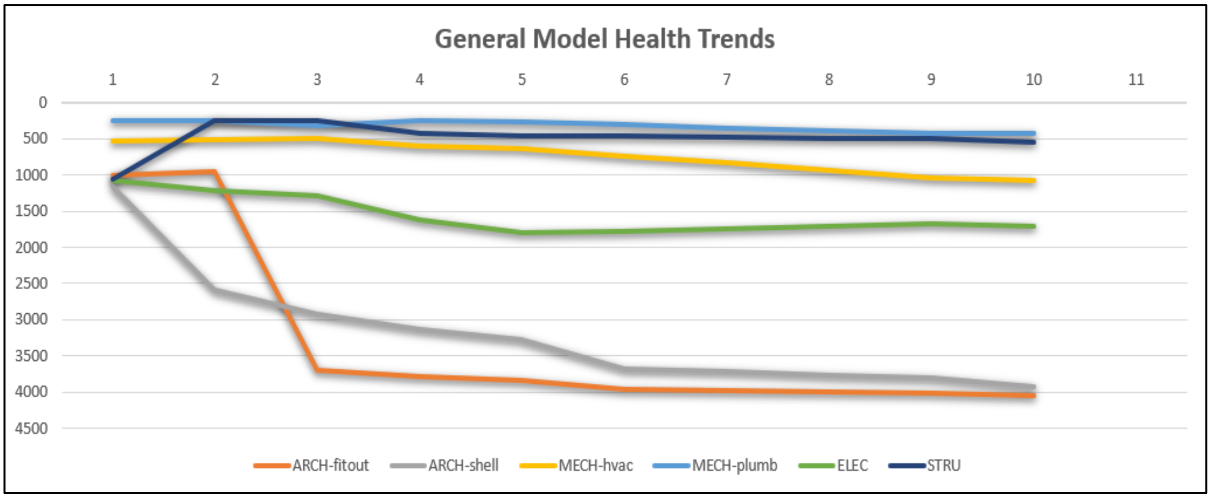



**Figure 4.13: Overall model health trends**

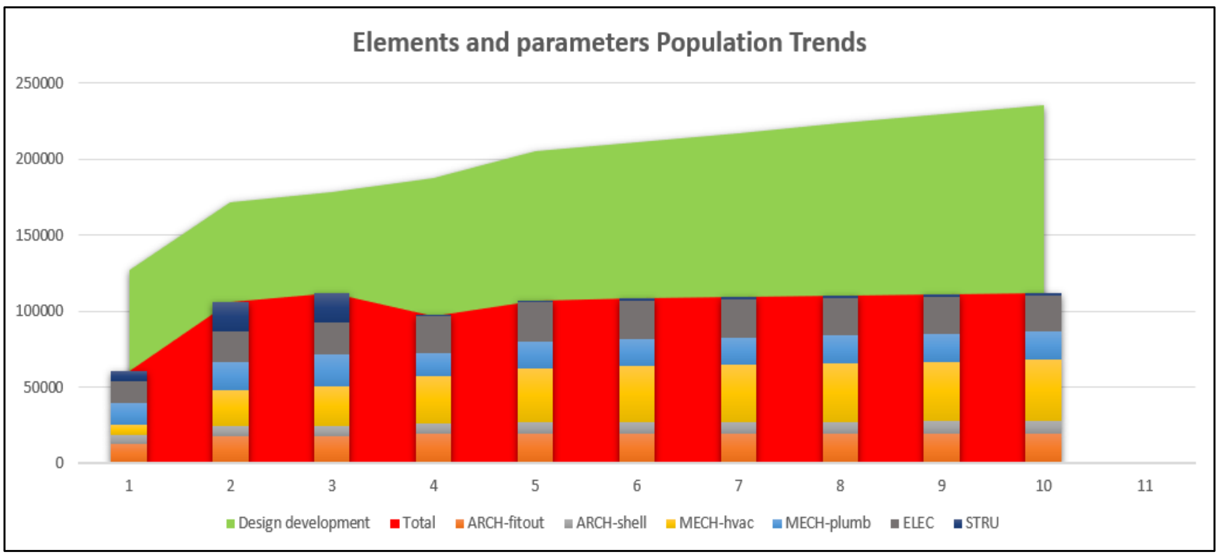



**Figure 4.14: Overall data compliance trends**

The trends were recorded and evaluated over the course of 5 months (10 bi-weekly data points). Figure 4.14 depicts that the proportion of the overall design development and the percentage of non-compliant elements (in red) was very high. The objective of having a steady decline in the non-compliant elements was not achieved over time, and non-compliance was observed to be stagnant over time. The design phase is expected to be a dynamic process, and the count of 3D elements increased over time while the compliance was not achieved.

### 4.1.5 Specifying the Lessons Learned

The design team faced issues with the ‘new’ tools, which were identified to streamline the compliance process through automated, rule-based compliance checks, easy information organization, and effective BIM data management. As discussed previously, one of the major barriers to BIM adoption is the overwhelming amount of technologies involved in the process. New and intelligent tools were identified by the Author to streamline the process. But it turned out that the introduction of these “new” tools, like intelligent BIM model checkers, etc. induced complexity in the BIM compliance process. BIM leads, designers, and engineers expressed a need to have a simple workflow that was very easy to execute and perceive. The project manager wanted a platform that had very low or almost no learning curve associated with it.

The Project Manager conveyed to the Author that the compliance reports generated by the intelligent and rule-based model checker are complex to read. The project manager faced difficulty in driving actions and assigning responsibilities to the team from such reports. The compliance reports generated were very inflexible and voluminous in nature. The Project Manager expressed a need to have an easy to understand, an executive one-page report that gives an overview of the overall compliance with the Owner’s BIM requirements.

BIM contained nearly a million data points that were to be used by the Owner to support construction and operations phase. The BIM data management tool was not observed to be time effective when dealing with such large data sets. While processing data sets of over 100,000 rows of data, the tool froze its functionality. Hence, a better computer processor might be required by all the team members when dealing with large data sets.

At the end of the AR cycle, an optimized technology-driven workflow for BIM data integration was developed to ensure compliance with the Owner's BIM requirements. Hence, the first AR cycle addressed the first objective of this research. The improvements were suggested from the lessons learned by the Author and the design team professionals. The lessons learned from this cycle were taken further to cycle 2 to address the overall needs of the design team, as shown in Figure 4.15. Effective BIM compliance management is achievable through correct expertise, processes, and tools in place. This enables the team to deliver the real value that was originally envisaged by the Owner. Also, there's a critical need for a 'simple consumer language' platform to clearly understand and manage the BIM compliance, which can further be used to drive compliance-related decisions.

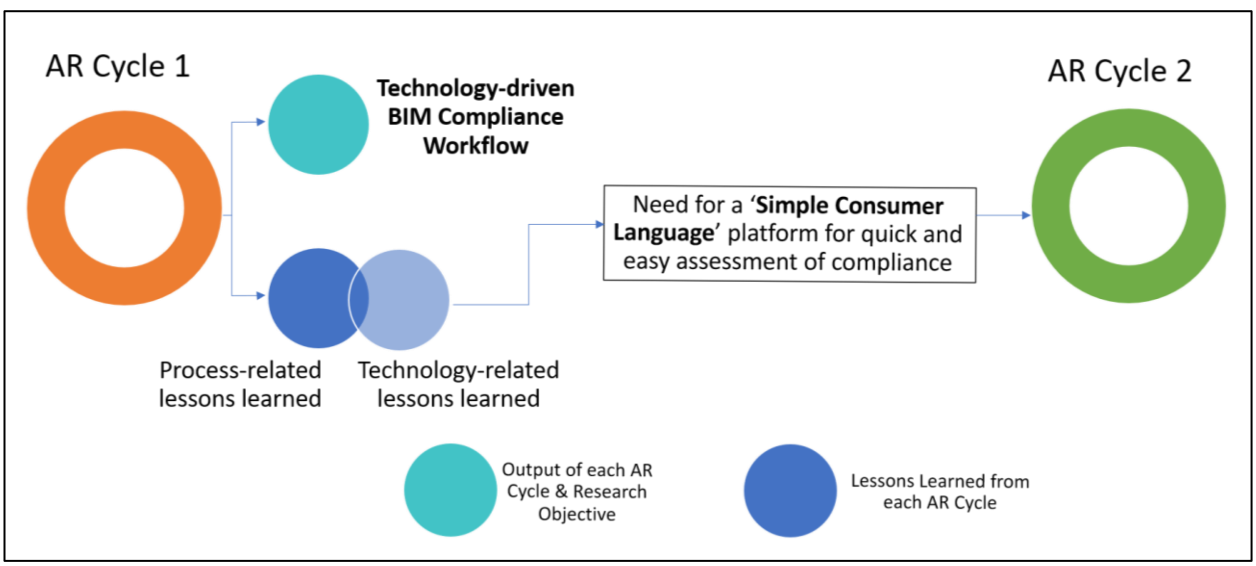



**Figure 4.15: Lessons Learned from AR Cycle 1 input to AR Cycle 2**

## 4.2 Action Research Cycle 2: Automated BIM Data Extraction and Parsing to Assess BIM and Data Quality using Visual Programming

In this AR cycle, the Author interrogates the API of the BIM authoring tool, parses and extracts the relevant BIM data to a 'simple and easy-to-understand' data analytics platform for quick and easy assessment of compliance. Figure 4.16 depicts the activities pursued in this AR cycle. The Author performed the second AR cycle in 1 month, that is, during the month of January 2018.

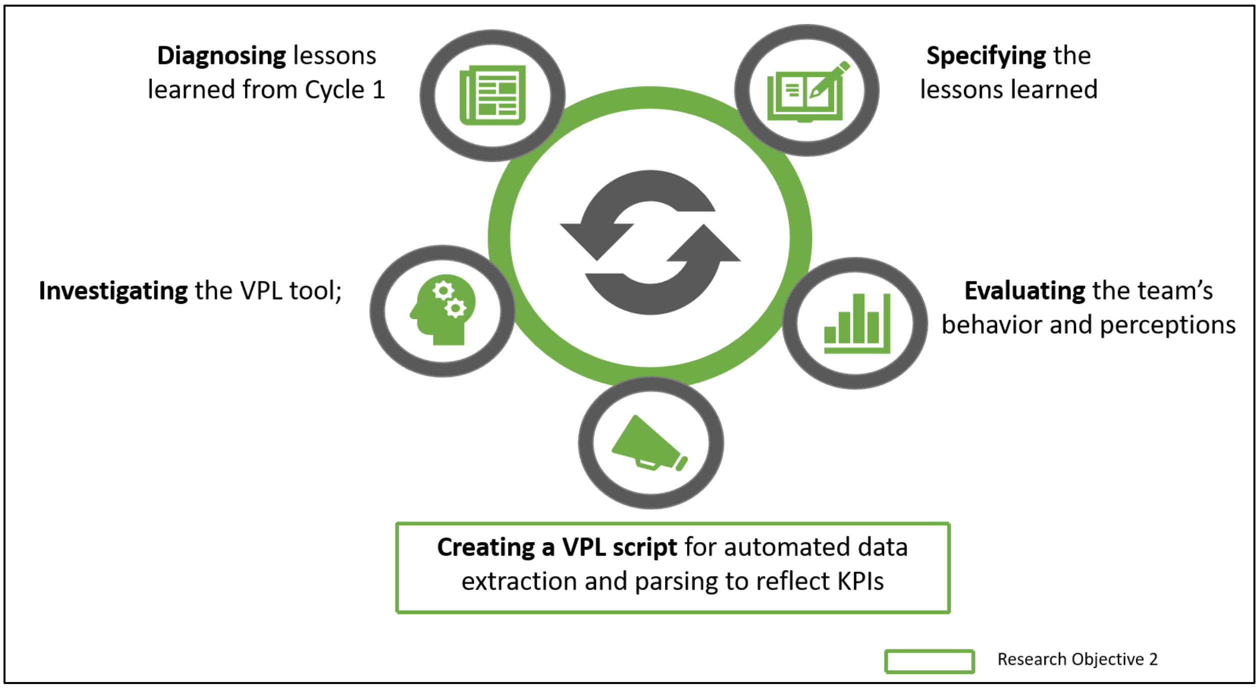



**Figure 4.16: Action research cycle 2 to address the second research objective (1 month)**

### 4.2.1 Diagnosing Lessons Learned from AR Cycle 1

The major learning from the first action research cycle was the project team's need for a simple, easy-to-understand platform to clearly understand the compliance, perform BIM quality checks (QC) and drive decisions.

The relevant design data contained in the BIMs to support overall BIM goals of the project exponentially grew with time. This growing trend made it difficult for the teams to extract and assess the right data sets for compliance. Also, the process of data extraction and compliance assessment was very frequent, and the BIM manager carried out this task manually on a bi-weekly basis. Hence, an automated system was required to help the team extract and parse the right data sets from the BIM to support compliance assessment in a simple platform.

As per the case study project's requirements, overall compliance is a composition of good model health and high information quality. BIM data management tools like "Ideate BIMlink" is great to access the non-graphical information of the elements but currently, it does not assess the model health data. Also, the efforts required to define the data that needs to be extracted and the time taken to extract such data is another limitation. Even though such tools eliminate redundant data entry, the time and processor required to process large datasets, nearly a million data points in this project, is very intensive. Also, the data management tools that are available facilitate only data extraction, and not the filtering and parsing. Those cleansing and parsing efforts are manual in the process and were observed to lead to errors and incorrect data integration.

### 4.2.2 Investigating the VPL Tool for Automated Data Extraction and Parsing

To achieve accessibility and flexibility with the relevant data required to assess compliance, the Application Program Interface (API) of the BIM authoring tool needs to be accessed. API enables a smooth communication with the software and all types of information can be accessed. Since it can be difficult for a beginner or average BIM user to use text-based scripting to access the API, Visual Programming language (VPL) is an uncomplicated way to streamline the process of automatic data extraction from the BIM. VPL does not require any computer programming or coding experience. It can also feed the extracted data into other data analysis applications for quick reviews and manipulation. VPL was used to streamline this tedious parametric data workflow on this project. A visual programming tool, called "Dynamo®", was used to widen the parametric functionality in the BIM authoring environments. A VPL script simply looks like a set of nodes connected by the sides, as shown in Figure 4.17 below.

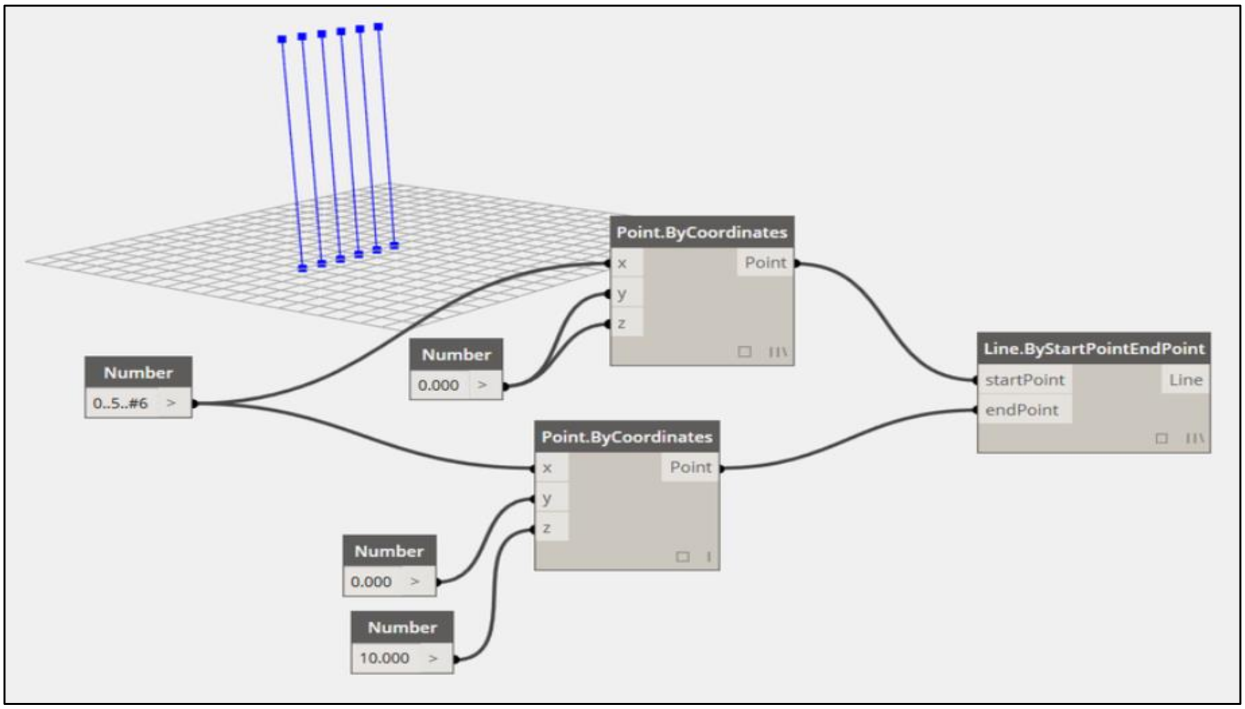



**Figure 4.17: Visual programming language script (Source: Autodesk Dynamo 2018)**

The nodes are predefined with the functions, inputs and outputs. A user simply needs to connect the right input and output ports to execute the script successfully. The input data can be fed into a node which gets manipulated by the predefined function of the node and then generated as the output data. A beginner or an average BIM user with limited or no programming language does not need to understand how the nodes are coded or created; they simply need to understand the input and manipulate nodes like a puzzle to produce the right outputs. No text-based scripting or lines of statements are required like a traditional programming environment to execute a program in VPL.

To understand the capacity of the tool, the Author began by investigating and understanding the performance of the tool when millions of data points are processed at once. The Author took about two weeks to get comfortable with the nodes, manipulating lists of data and getting the required data output. The tool offers endless opportunities to manipulate data and append a relevant piece of information before feeding the output to the data analysis software. The processing time for large datasets was noted of about a few minutes, which was satisfactory. After investigating for two weeks, the Author concluded this to be the best option available for an intermediate BIM user to automatically extract, manipulate and parse data in minutes, thus streamlining the tedious parametric data workflows. Also, once the script is created, anyone on the project team who has access to the building information model can run this script and get data in just one click. The Author aimed to create the following workflow:

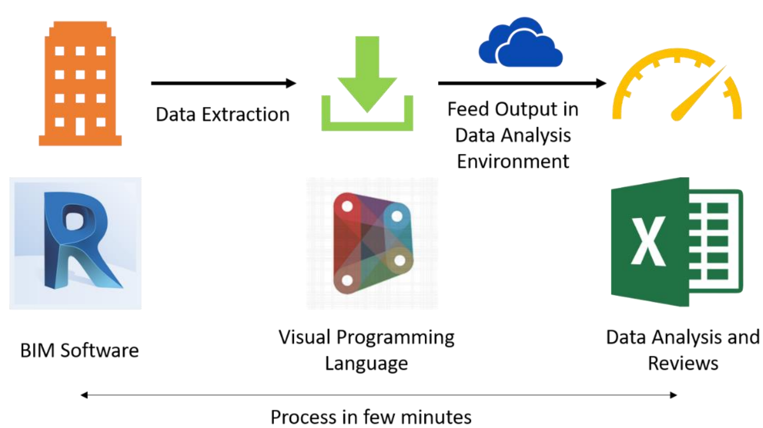



**Figure 4.18: Anticipated VPL script workflow**

### 4.2.3 Developing a VPL Script to Automate Data Extraction and Parsing for Compliance Assessment

The idea behind utilizing VPL was to enhance the accessibility and flexibility with the extraction and parsing of data, thus streamlining the second phase of BIM compliance. To effectively use the tool and streamline the workflow, the Author laid down a roadmap for creating a right and valuable script. The following describes the activities that were planned.

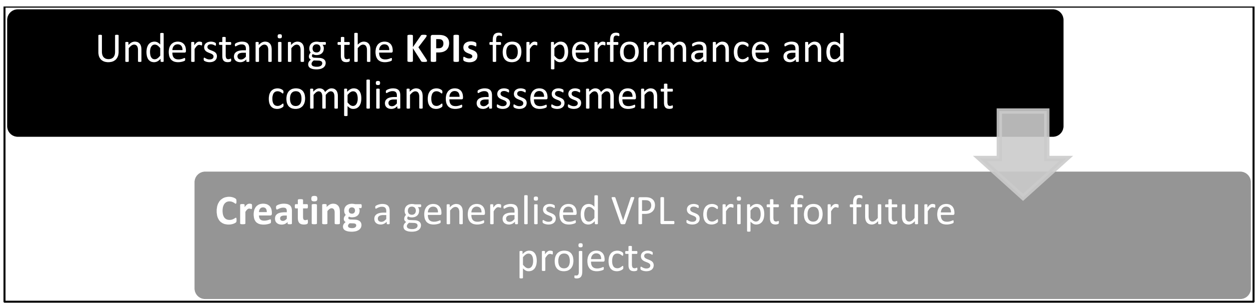



**Figure 4.19: Roadmap to creating VPL script for automated data extraction and parsing**

#### 4.2.3.1 Understanding the KPIs for Performance and Compliance Assessment

The objective was to extract the data from the models that holds value to the project team. After being satisfied with the language and the tool, the next step was to understand what needs to be measured for the BIM model's performance assessment and compliance management. To streamline the tedious data extraction workflow for future projects, it was important to understand the data types that can generally be attributed towards compliance and performance. Thus, the Author conducted a meeting with the Regional BIM Lead and the BIM Manager on the project to understand the key performance measures (KPIs) that needs to be tracked to assess the compliance with organization's BIM standards and project's BIM requirements. KPIs were required to help the professionals spend more time on critical and valuable activities that drive performance and compliance and less time on the activities that are less relevant. Table 4.3 summarizes the KPIs that were required to be tracked for compliance assessment. The impact of each KPI is explained in detail in Section 4.3.4.1 and Section 4.3.4.2 of this chapter.

**Table 4.3: Key Performance metrics (KPIs) for BIM performance and compliance assessment**

| Type | Category | KPI for Compliance Assessment | Impacts |
|---|---|---|---|
| **BIM Health Metrics** | **Model Representation** | BIM Warnings and Impacts | Stability, speed, and accuracy of BIM model |
| | | Sudden Fluctuations in Model File Size | Data corruption; Content Loss |
| | | Presence of In-place Families | Owner's BIM requirement |
| | | Unused Elements | Model performance |
| | | Schedule of Project Views Not Available on Sheets | Meaningful and cleaner project; Model file performance |
| | | View Templates Not Available on the Views on Sheets | Consistency in construction document sets; Owner's visual quality checks |
| | | Unplaced Model Groups | Consistency among repeated objects; Streamline design iterations; Model performance |

| | | | |
|---|---|---|---|
| | | Overall Development of 3D Elements over Time | Assess team's efforts towards BIM compliance |
| | **Model Classification and Nomenclature** | Presence of Restricted Naming Conventions of Designed Elements | Information handover over project phases; Owner's BIM requirement |
| | | Restricted Objects in BIM Models | Consistency of graphics and data control of the 3D objects |
| **BIM IQ Metrics** | **IQ Dimensions** | Data Incompleteness | Owner's BIM requirement; Project Risk |
| | | Data Duplication | Owner's BIM requirement; Project Risk |
| | | Data Inconsistency | Owner's BIM requirement; Project Risk |
| | | Data Inaccuracy | Owner's BIM requirement; Project Risk |

#### 4.2.3.2 Creating a Generalized VPL Script for Future Projects

After understanding the KPIs that needs to be tracked, the Author began creating a VPL script in Autodesk Dynamo that processes the required data. The aim was to configure a script that allows the team to export all the needed data to a live excel file, where the end user can quickly review the data. The Author planned to parse the data in the background of the script. Various open source nodes were used by the Author to create a robust yet straightforward script.

Following trials and errors on the rule-based scripting for almost a month, the Author created a script that tracked all the required KPIs for performance and compliance assessment. The

Author appended a unique identification parameter "*ID*" of each element to the output to provide flexibility and accessibility to search the non-compliant component in the BIM authoring environment. This helped in creating a two-way connection between the BIM authoring tool and data output in excel file.

A snapshot of the script is provided in Figure 4.21. In comparison to the time-intensive and manual traditional process, this script took less than 5 minutes to process millions of rows of data and pushed the output in the spreadsheets placed on cloud storage for easy sharing and accessibility.

### 4.2.4 Evaluating the Team's Behavior and Perceptions

After creating the script, the entire automation process was demonstrated to the project team. The Author received positive feedback from all the potential users however, the project manager found the script very intimidating. Also, the project manager mentioned that they do not access the BIM models directly and depend upon a BIM professional to share the insights on performance and compliance. The output of this script was perceived as overwhelming, challenging for the PM team to read and drive decisions. They expressed further need to develop a platform that converts the BIM jargon to simple consumable language. No massive updates were required to the script and the Regional BIM lead expressed a need to use this script on all the future project that the company will work upon. After satisfying most of the team members, the Author moved further to develop a simple consumable platform that the PM team can use to assess performance and compliance and drive their decisions accordingly.

### 4.2.5 Specifying the Lessons Learned

Visual Programming Language (VPL) has been used widely in the past years for parametric and computational design. VPL offers a valuable way to deal with the extraction, manipulation, and parsing of a gigantic piece of information in a few minutes. Using the API, this tool can access all types of information contained in the BIM models thus offering limitless opportunities. It can also access the information contained in multiple linked models, thus saving the redundancy in the opening and closing of multiple models. The script offers similar execution and performance even though data grows exponentially in the BIM models during design development. The BIM manager on the project moved from bi-weekly manual extraction and parsing to automated extraction and parsing of data using this VPL script. As discussed in the case study chapter of this thesis, the traditional method of manual data extraction took about 2 days per BIM model but using this script the processing time was significantly reduced to about a few minutes. Therefore, an automated system was created by the Author to help the team extract and parse right data sets from the BIM model to streamline performance and compliance assessment workflows.

At the end of the AR cycle 2, the Author realized there was a disconnect in the way the information is presented in the BIM delivery through an informal discussion with the design consultant's Project Manager. The Author observed that the consumers of the compliance reports did not have the required skills to understand the BIM terminology to access the status of compliance and evaluate performance. As a result, the Author created a robust VPL script which exported all the required data to a data analytics platform, Microsoft Excel spreadsheets, and presented the non-compliant elements that need to be fixed in a clear and concise manner. The team members with limited understanding perceived these spreadsheets as very difficult to understand and drive actions.

Due to the inundation of data and limited understanding of BIM technology platform, the project management team was not able to quantify the performance and the impact of its consequences. A clarity on current state could not be perceived as well. As a result, the team was unable to support the BIM expert's efforts on mitigating model health issues, maintain high information quality and help manage expectations. The project manager was interested in a platform that can quickly transform the BIM jargon to a generalized and simple consumable information. As shown in Figure 4.20, the lessons learned from AR cycle 2 were carried forward towards AR cycle 3.

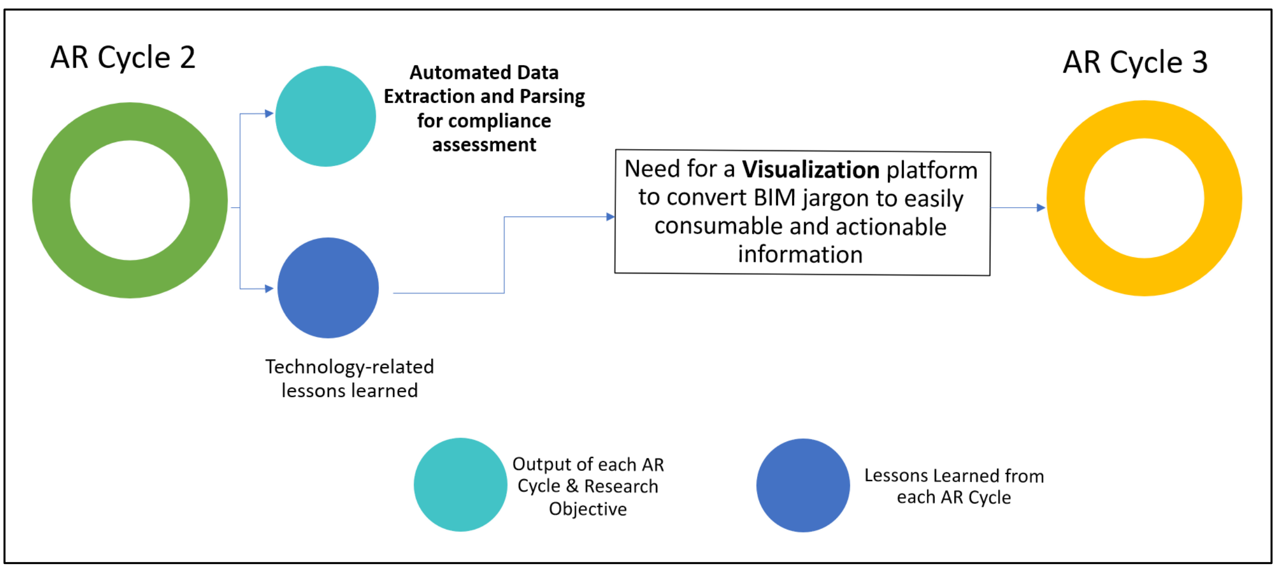



**Figure 4.20: Lessons Learned from AR Cycle 2 input to AR Cycle 3**

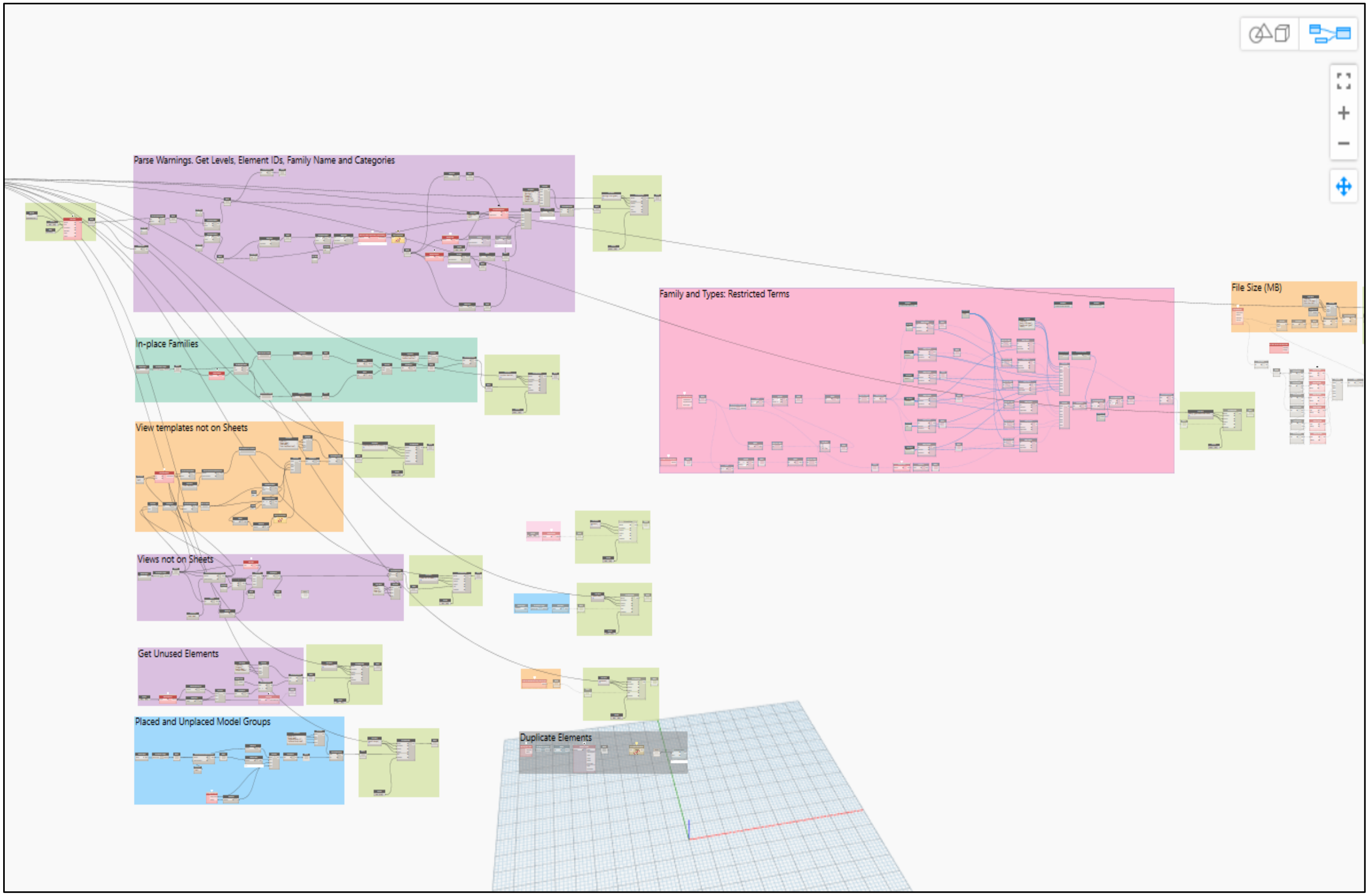



**Figure 4.21: VPL Script for automated BIM data extraction for BIM compliance assessment**

## 4.3 Action Research Cycle 3: Interactive Visual Analytics for Compliance Assessment and Decision-Making

Action research was used to address the third research objective to develop a simple platform to provide a clear understanding of BIM compliance through visualization analytics. The Author and the project's design team performed this action-research cycle over a 3-months period, during the duration of this study from February 2018 to April 2018. As shown in Figure 4.22 below, the following research activities were carried out in this AR cycle.

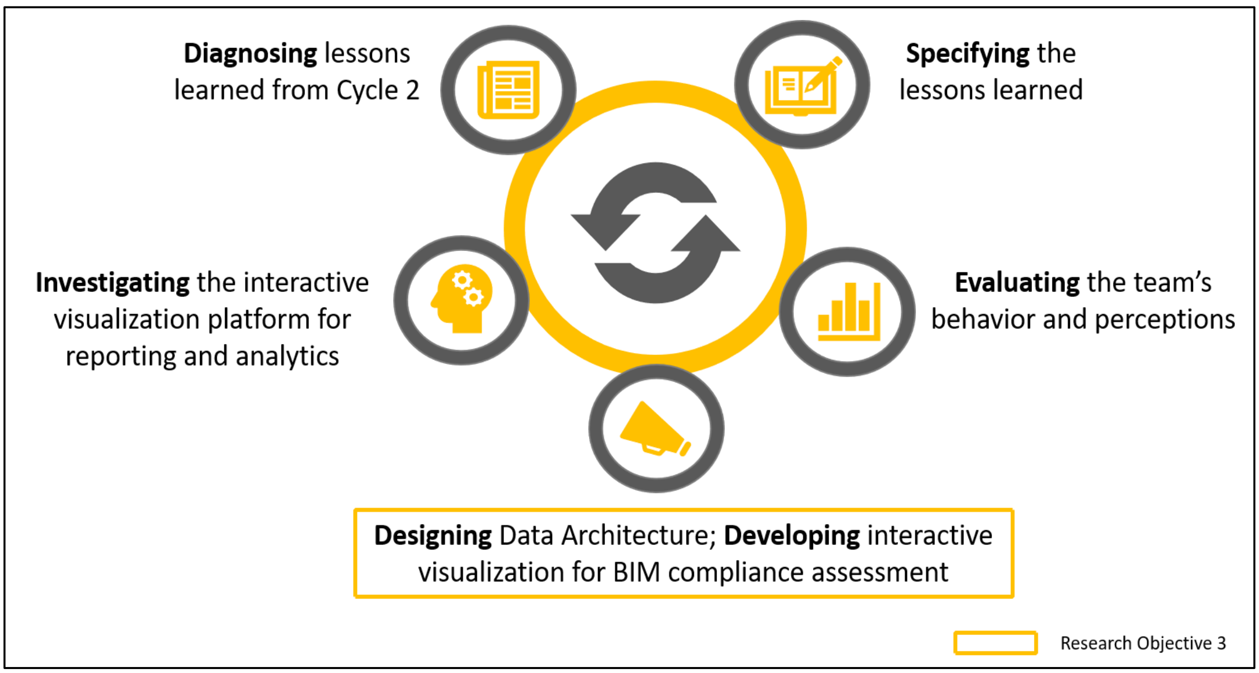



**Figure 4.22: Action research cycle 3 to address third research objective (3 months)**

### 4.3.1 Diagnosing the Lessons Learned from Cycle 2

Project Management is expected to maintain the lines of communication between all the parties involved in a project, manage expectations for delivery and timeline, and provide support and gentle push to the teams to fulfill the project requirements. To successfully fulfill these responsibilities, the managers need structured information in an easy to read format that supports reporting and analysis. Concerning compliance with the Owner's BIM requirements (or BIM Compliance), such measures were not observed to be efficiently taken by the project management team during the design phase of this project. At the end of the AR cycle 2, the Author conducted an informal discussion with the design consultant's Project Manager and realized a disconnect in a way the information is presented in the BIM delivery. During the discussion, the project manager conveyed to the Author that having a visualization platform would help in maintaining "one version of the truth" for the team, thus enabling them to make informed decisions to keep forward progression.

### 4.3.2 Investigating Visualization Tools for Reporting and Analytics

In an information-rich environment, for the managers to make the best possible decisions in the optimum amount of time, it is pivotal to transform and present the unperceivable data as structured and actionable information to support object-oriented reporting and analysis. Over the recent years, various industries have tackled this problem using Business Intelligence (BI) tools like 'Dashboards', which support reporting and analytics through interactive visualization (Rasmussen, Bansal, and Chen 2009). Dashboards significantly reduce the need for enormous reports on spreadsheets, supports better decision making and helps improve overall performance. "Since the dashboards are highly graphical, dynamic, and easy to use, with simple training users across an organization can be empowered to monitor and analyze the information relevant to the areas of responsibility and to make informed decisions" (Rasmussen, Bansal, and Chen 2009).

Similar to the dashboard available in a car that reports the vital information about speed, temperature, fuel level and so on, the project business dashboard reports the KPIs to help the team execute their projects in an informed manner. The project team can quickly discover problems and take necessary action to help improve the performance. In terms of compliance, the dashboard reports the status, the target, and the timeline to achieve the target.

The data collection point for the dashboard was the data analysis software, Excel spreadsheets, where the VPL script pushed the data from BIM models. The next step was to use a BI software that seamlessly works with this data analysis software, Microsoft Excel, and requires very little data transformation to create visualizations. Microsoft Power BI was used to create the interactive data visualizations, or dashboard. Power BI can create visually appealing personalized reports which can then be published to the consumers over the cloud, web or across mobile devices. Figure 4.23 below shows the user interface of Power BI desktop. As it can be seen below, dashboards with similar look and feel can be created using this software.

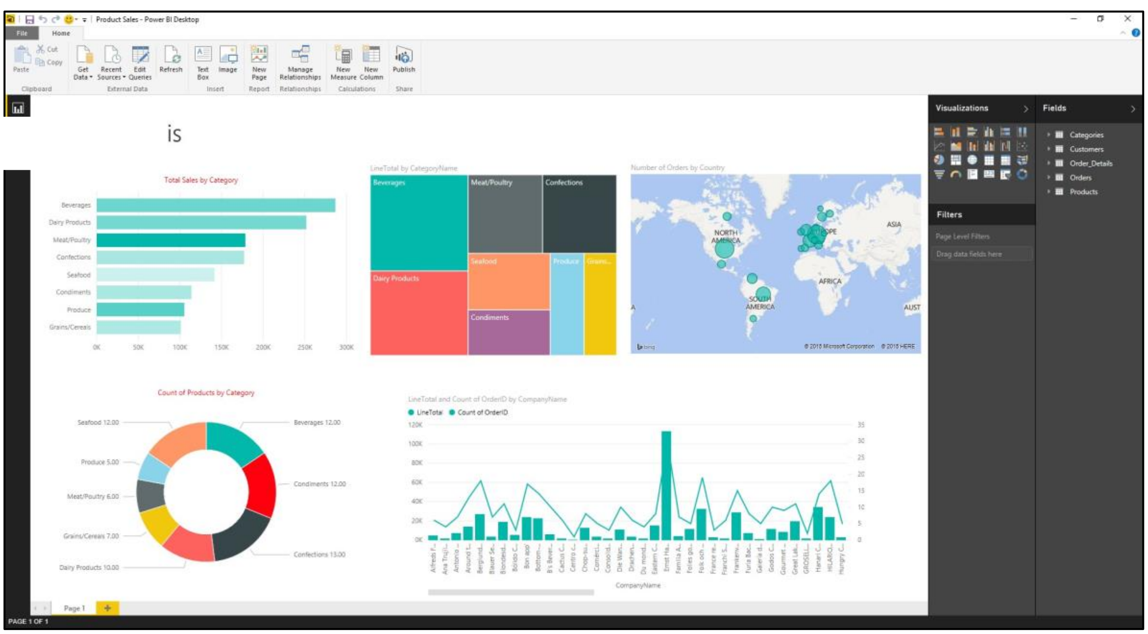



**Figure 4.23: Microsoft Power BI desktop user interface (Source: Microsoft Power BI)**

### 4.3.3 Designing Data Architecture and Developing the Visualizations

To transform BIM jargon in structured information and present in an actionable manner, the Author laid down a roadmap to creating the final product for the team. The activities were carried out as follows:

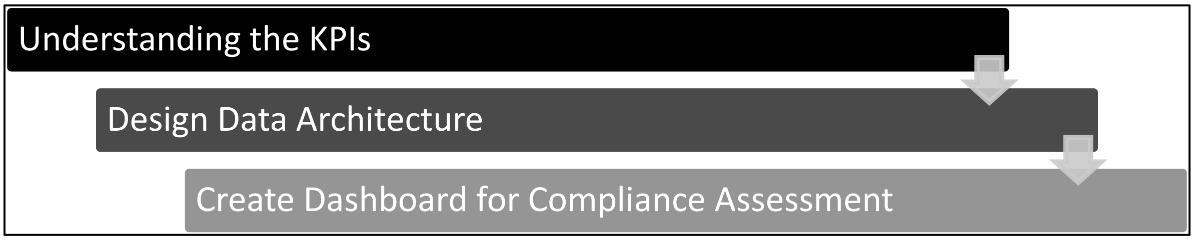



**Figure 4.24: Roadmap to developing a dashboard for compliance assessment**

#### 4.3.3.1 Understanding the KPIs

The first step in developing an interactive visualization dashboard for compliance management was understanding the key metrics which are attributable to compliance with the Owner's BIM requirements. Dashboards optimize the business (or project) performance by presenting the valuable metrics for monitoring and analysis to the consumers through a powerful interface. The KPIs were retrieved by the Author from a discussion with the Regional BIM Lead and the BIM Manager on the project. A list of KPIs is presented in Table 4.3.

Once the KPIs were finalized, the next sub-step was to automate the process of data extraction from the BIM models and feeding into the BI platform. The automated data extraction and parsing process set up by the Author exported the required KPI information from the BIM models to data analysis software in a few minutes. This last step of data extraction was planned to become the data collection step for the dashboard. The idea was to analyze and utilize this information and create a dashboard for reporting the KPIs.

#### 4.3.3.2 Design Data Architecture

Data architecture, content, and functionality of the dashboard are critical success factors to interactive visualization analytics implementation. The main purpose of this interactive visualization platform was to provide a simple and easy to understand reporting of compliance to the project team for quick analytics and decision-making. This dashboard was to be designed to reflect a periodic status, not real time. For effective reporting, the Author wished to provide a simple structure to the dashboard and not overload the dashboard with numerous visualizations and random data graphics. Concerning compliance, the Author planned to divide the dashboard mainly into two parts:

a. BIM Model health Report
b. BIM Information Quality Report

Each of these reports represented compliance in poor, good or excellent manner. A color consistency was to be maintained for the consumers to quickly perceive the areas of poor compliance (in RED). The following color categorization was used to help the managers understand the health and in cases of poor or unsatisfactory health, support them to direct the remediation tasks to the design team and fix the issues right-away.

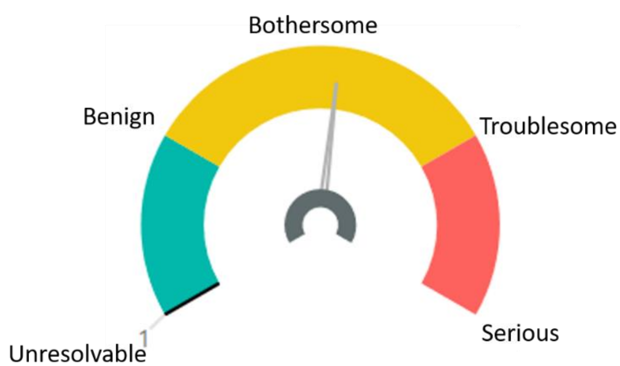



**Figure 4.25: Example of color consistency and clear meaning to graphics in dashboard**

#### 4.3.3.3 Create Dashboard for Compliance Assessment

Once the KPIs, BI tool and the data architecture was finalized, the Author began creating the dashboard. The first step was to link the data sources, that is, linking the output of VPL to the BI tool. Once the data was linked, various queries had to be defined to create graphics and interactive visualizations. A snapshot of architectural design data query is provided in the Figure 4.26 below. An advanced query editor allows the user to define and transform data operation on the data source, without affecting the original data source.

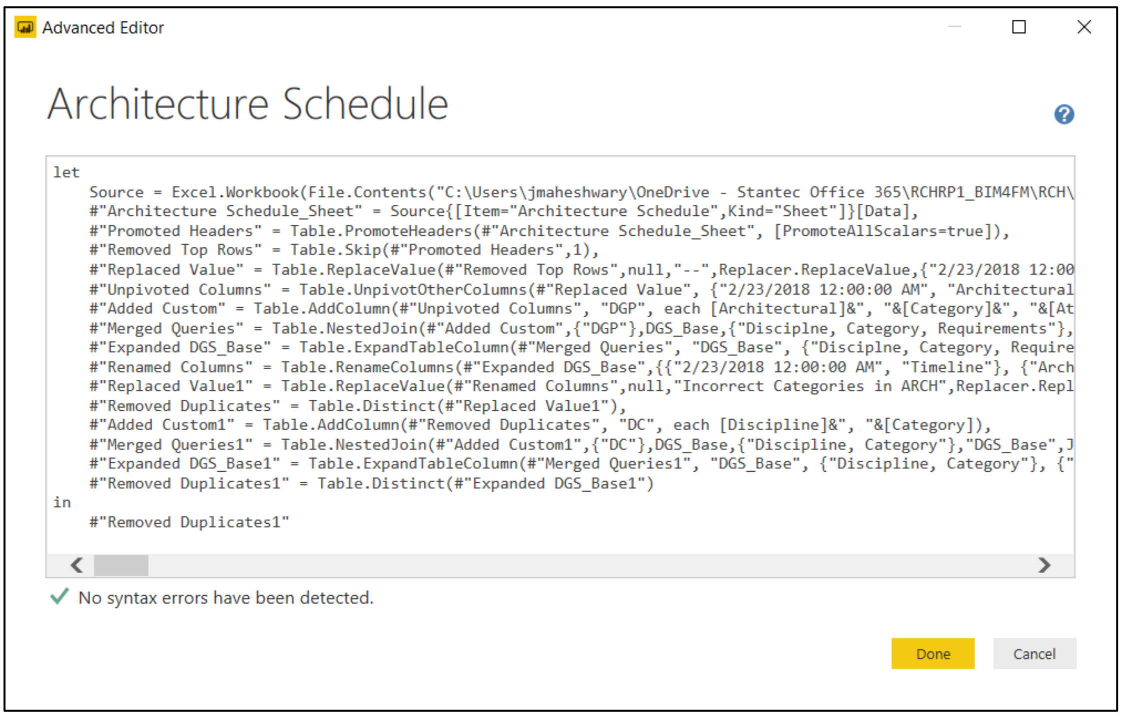



**Figure 4.26: Microsoft Power BI data query advanced editor for data transformation**

The data had to be transformed for creating graphics and visualizations. Once the rows of data were cleansed, pivoted and transformed, the data graphs were generated for each KPI. Each graphic is discussed in detail in the next section.

A snapshot of the 'BIM Compliance Summary' page of the interactive visualization platform (or dashboard) is provided below in Figure 4.27. The summary page was intended for the higher management to review and assess the status of compliance on the project.  shows the discipline-specific (Architectural) status of compliance, intended for the BIM leads and BIM manager on the project. Figure 4.29 shows the page of the dashboard that can be used to review the BIM data integrated with the BIM models and assess information quality for compliance. Different IQ dimensions like incompleteness, inaccuracy, understandability, and inconsistency can be reviewed using this page. The graphics provided on the left side of the table of report can be used to filter down the data using the categories (like doors, walls, etc.) or using the Owner specified parameters (like mark, equipment ID, etc.) that were intended to be used to drive construction and operations of the facility.

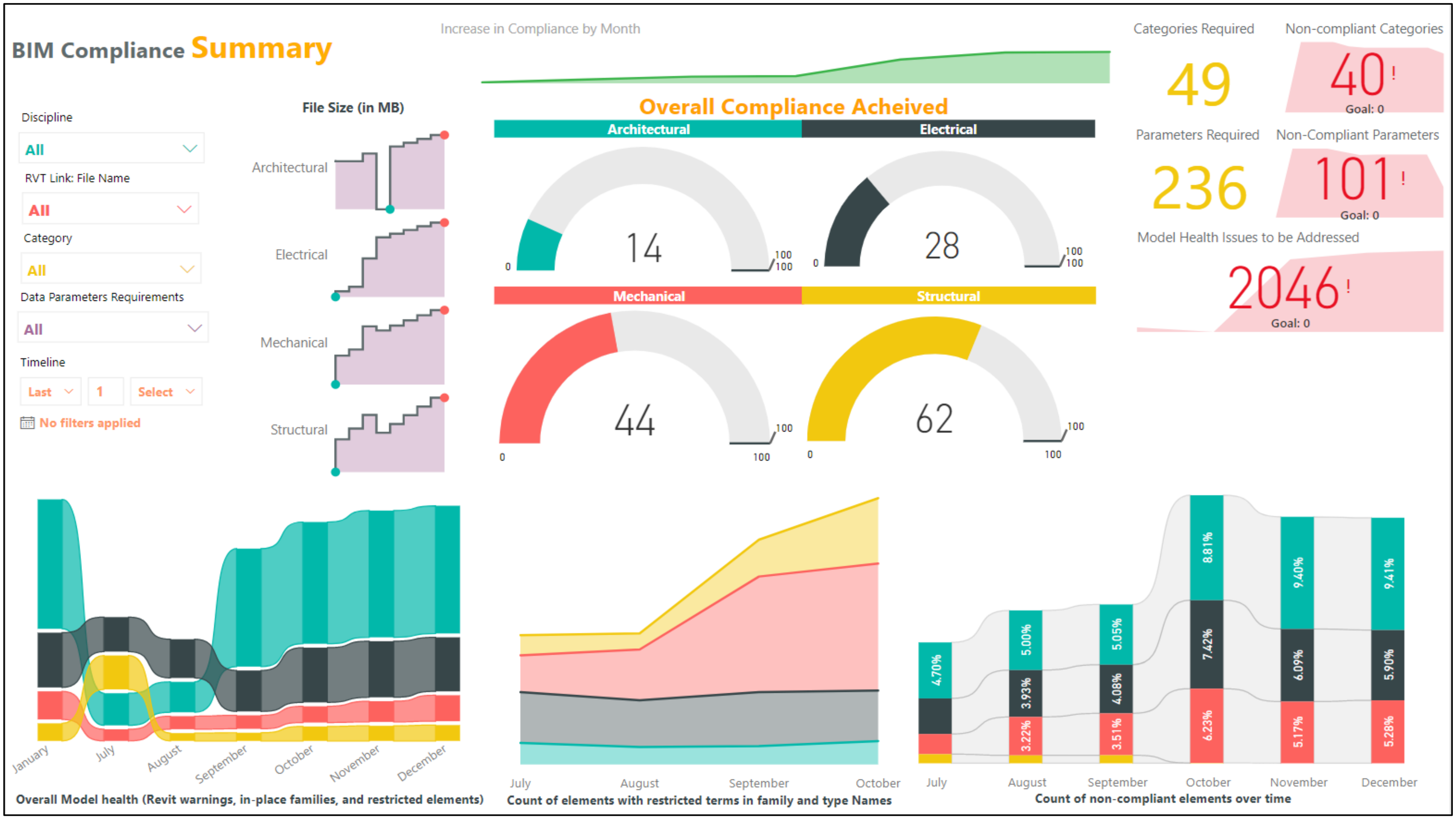



**Figure 4.27: Overall report for compliance assessment with the Owner's BIM requirement. This reports the summary of overall BIM model health and BIM data quality issues. All the graphics presented above reflect the status of compliance with the Owner’s BIM requirements on the project.**

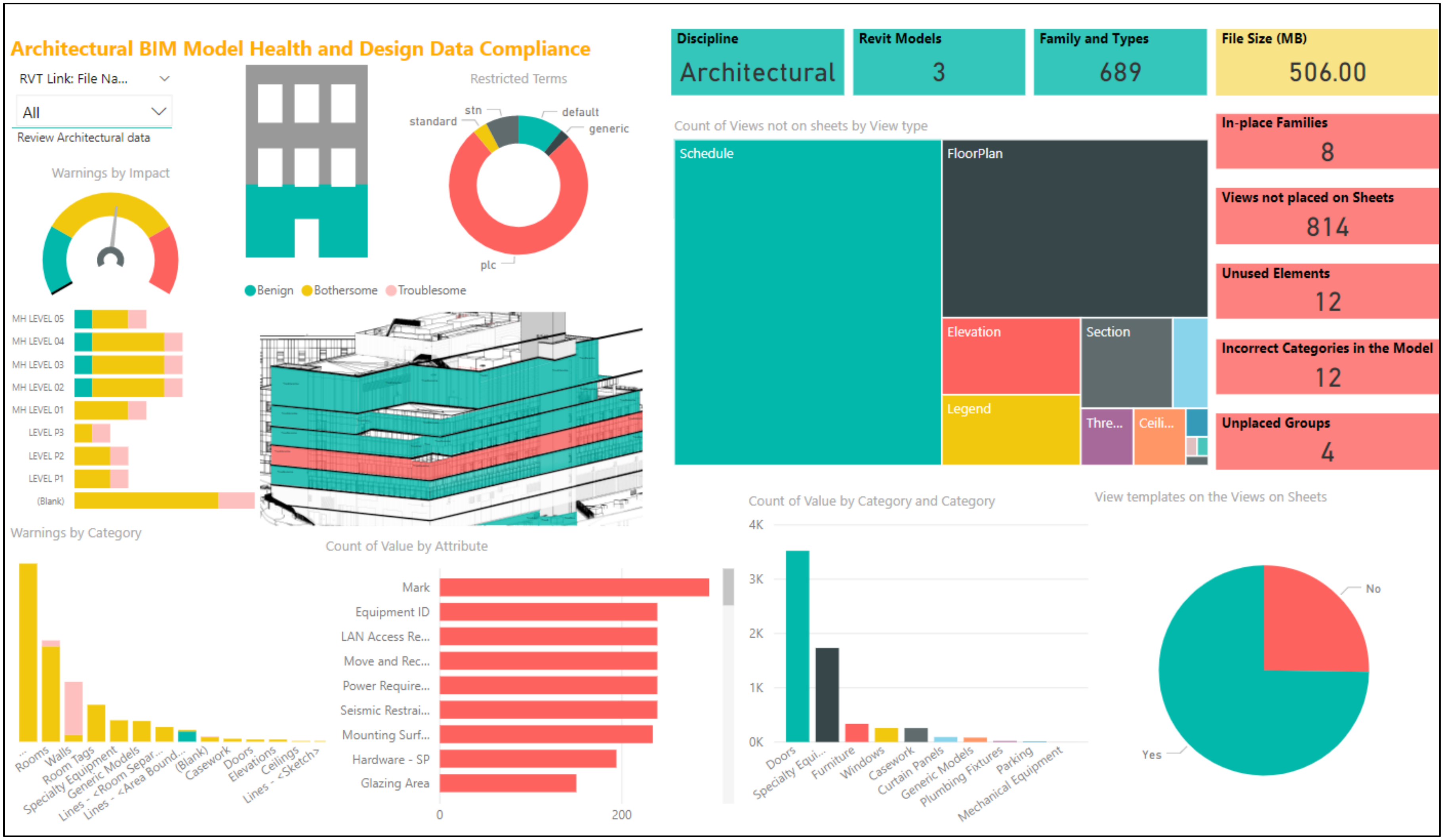
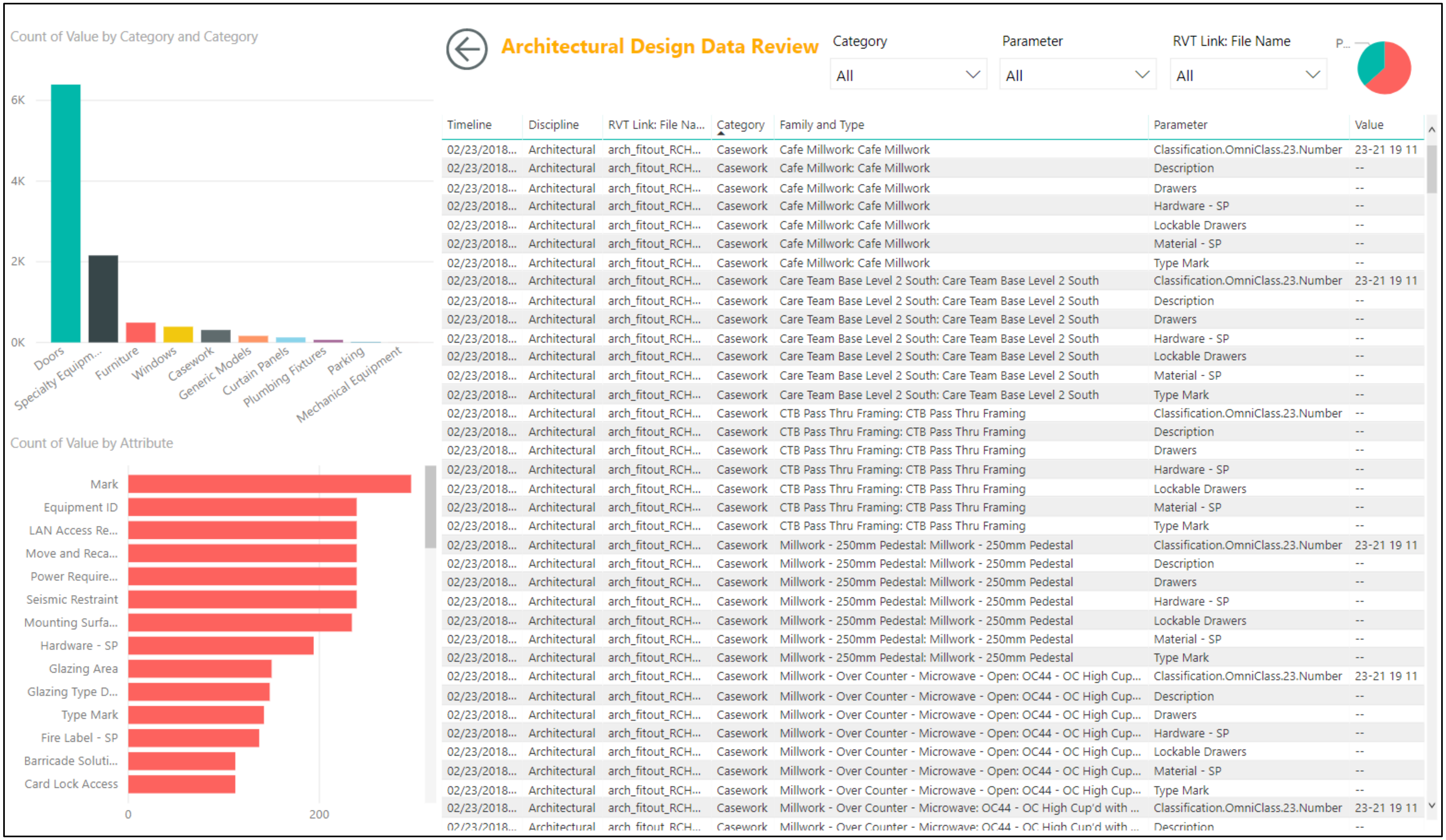



**Figure 4.28: Architectural BIM health and design data compliance assessment report. All the graphics represent KPI for compliance with the Owner's BIM requirements. KPIs include BIM warnings, data completeness, data understandability (restricted terms), BIM model views, in-place families, unused elements, unplaced mass elements, and a hyperlink to 'Review Architectural Data' for data quality reviews.**




| Timeline | Discipline | RVT Link: File Na... | Category | Family and Type | Parameter | Value |
|---|---|---|---|---|---|---|
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Cafe Millwork: Cafe Millwork | Classification.OmniClass.23.Number | 23-21 19 11 |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Cafe Millwork: Cafe Millwork | Description | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Cafe Millwork: Cafe Millwork | Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Cafe Millwork: Cafe Millwork | Hardware - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Cafe Millwork: Cafe Millwork | Lockable Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Cafe Millwork: Cafe Millwork | Material - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Cafe Millwork: Cafe Millwork | Type Mark | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Care Team Base Level 2 South: Care Team Base Level 2 South | Classification.OmniClass.23.Number | 23-21 19 11 |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Care Team Base Level 2 South: Care Team Base Level 2 South | Description | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Care Team Base Level 2 South: Care Team Base Level 2 South | Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Care Team Base Level 2 South: Care Team Base Level 2 South | Hardware - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Care Team Base Level 2 South: Care Team Base Level 2 South | Lockable Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Care Team Base Level 2 South: Care Team Base Level 2 South | Material - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Care Team Base Level 2 South: Care Team Base Level 2 South | Type Mark | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | CTB Pass Thru Framing: CTB Pass Thru Framing | Classification.OmniClass.23.Number | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | CTB Pass Thru Framing: CTB Pass Thru Framing | Description | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | CTB Pass Thru Framing: CTB Pass Thru Framing | Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | CTB Pass Thru Framing: CTB Pass Thru Framing | Hardware - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | CTB Pass Thru Framing: CTB Pass Thru Framing | Lockable Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | CTB Pass Thru Framing: CTB Pass Thru Framing | Material - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | CTB Pass Thru Framing: CTB Pass Thru Framing | Type Mark | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - 250mm Pedestal: Millwork - 250mm Pedestal | Classification.OmniClass.23.Number | 23-21 19 11 |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - 250mm Pedestal: Millwork - 250mm Pedestal | Description | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - 250mm Pedestal: Millwork - 250mm Pedestal | Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - 250mm Pedestal: Millwork - 250mm Pedestal | Hardware - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - 250mm Pedestal: Millwork - 250mm Pedestal | Lockable Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - 250mm Pedestal: Millwork - 250mm Pedestal | Material - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - 250mm Pedestal: Millwork - 250mm Pedestal | Type Mark | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave - Open: OC44 - OC High Cup... | Classification.OmniClass.23.Number | 23-21 19 11 |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave - Open: OC44 - OC High Cup... | Description | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave - Open: OC44 - OC High Cup... | Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave - Open: OC44 - OC High Cup... | Hardware - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave - Open: OC44 - OC High Cup... | Lockable Drawers | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave - Open: OC44 - OC High Cup... | Material - SP | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave - Open: OC44 - OC High Cup... | Type Mark | -- |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave: OC44 - OC High Cup'd with ... | Classification.OmniClass.23.Number | 23-21 19 11 |
| 02/23/2018... | Architectural | arch_fitout_RCH... | Casework | Millwork - Over Counter - Microwave: OC44 - OC High Cup'd with ... | Description | -- |

**Figure 4.29: Discipline-specific report for quick and easy BIM data quality review. Different dimensions of information quality can be reviewed manually in the 'Value' column of this report. The graphics represent the incomplete data in categories (like doors, walls, etc.) and parameters (mark, equipment ID, etc.) explicitly required by the Owner to drive construction and operations phase of the project**

### 4.3.4 Evaluating Team's Behavior and Perceptions

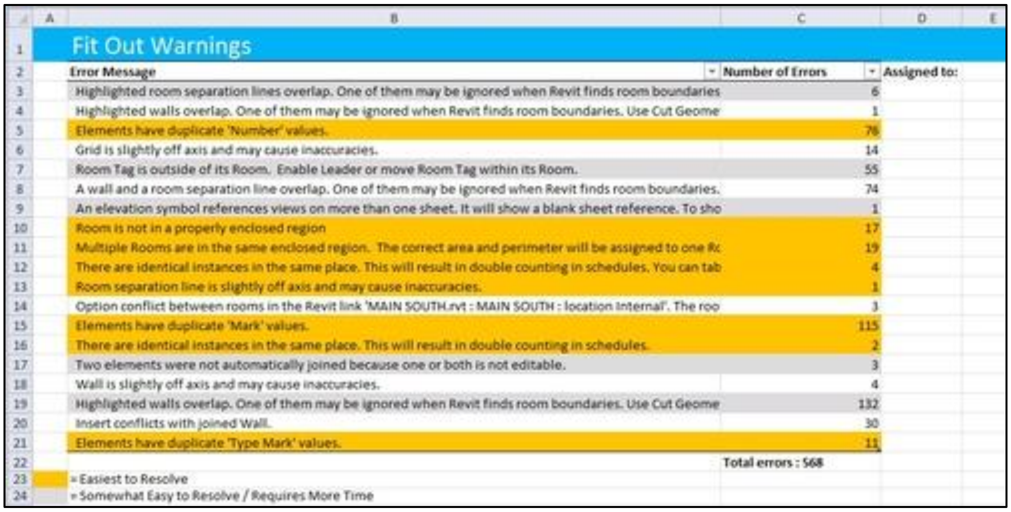
Once the visualizations were created, the Author demonstrated the functionality of the dashboard to the design and project management team. Each graphic represented a KPI that were listed by the BIM lead and BIM manager on the project. Also, the status of compliance with all the Owner's BIM requirements were represented on this dashboard. Figure 4.27, Figure 4.28, and Figure 4.29 are provided above that represents the key reporting pages of the dashboard. Each page had a various graphics, created in reliance with the KPIs, which were categorized and demonstrated as follows:

#### 4.3.4.1 BIM Model Health Metrics

**1. BIM Model Warnings and its Impacts**

BIM model warnings are the messages that show the deviations from expected best modeling practices. These warnings impact the performance of the model, specifically the stability and accuracy of the modelled content in the BIM models. The warnings should be periodically reviewed by the CAD technicians, designers, BIM leads and BIM managers to evaluate performance and solved to the limits possible.

Warnings encompass various inaccuracies and duplication issues in the BIM content, as shown in Figure 4.30. For example, "Elements have duplicate 'Number' values", "Multiple Rooms are enclosed in the same region", "Elements have duplicate 'Mark' values", etc.



**Fit Out Warnings**

| Error Message | Number of Errors | Assigned to: |
|---|---|---|
| Highlighted room separation lines overlap. One of them may be ignored when Revit finds room boundaries | 6 | |
| Highlighted walls overlap. One of them may be ignored when Revit finds room boundaries. Use Cut Geome | 1 | |
| Elements have duplicate 'Number' values. | 76 | |
| Grid is slightly off axis and may cause inaccuracies. | 14 | |
| Room Tag is outside of its Room. Enable Leader or move Room Tag within its Room. | 55 | |
| A wall and a room separation line overlap. One of them may be ignored when Revit finds room boundaries. | 74 | |
| An elevation symbol references views on more than one sheet. It will show a blank sheet reference. To sho | 1 | |
| Room is not in a properly enclosed region | 17 | |
| Multiple Rooms are in the same enclosed region. The correct area and perimeter will be assigned to one Rc | 19 | |
| There are identical instances in the same place. This will result in double counting in schedules. You can tab | 4 | |
| Room separation line is slightly off axis and may cause inaccuracies. | 1 | |
| Option conflict between rooms in the Revit link 'MAIN SOUTH.rvt : MAIN SOUTH : location Internal'. The roo | 3 | |
| Elements have duplicate 'Mark' values. | 115 | |
| There are identical instances in the same place. This will result in double counting in schedules. | 2 | |
| Two elements were not automatically joined because one or both is not editable. | 3 | |
| Wall is slightly off axis and may cause inaccuracies. | 4 | |
| Highlighted walls overlap. One of them may be ignored when Revit finds room boundaries. Use Cut Geome | 132 | |
| Insert conflicts with joined Wall. | 30 | |
| Elements have duplicate 'Type Mark' values. | 11 | |
| | Total errors : 568 | |

= Easiest to Resolve
= Somewhat Easy to Resolve / Requires More Time

**Figure 4.30: BIM model warnings exported to Microsoft Excel for quick reviews. Rows with easy to resolve 'Inaccuracy' issues highlighted in yellow.**

Figure 4.31 shows the graphic used to categorize model warnings by its impacts on the speed, stability and accuracy in the BIM model. This provides an overview of the performance of the models to the project team. Figure 4.32 shows the graphics used to categorize the model warnings and its impacts by building levels and Autodesk Revit Categories (like rooms, doors, walls, MEP spaces, etc.). Categorization by levels was provided for the team members responsible for specific areas for resolution and help project management keep a track of the frequency at which the levels with high impacts require model maintenance.

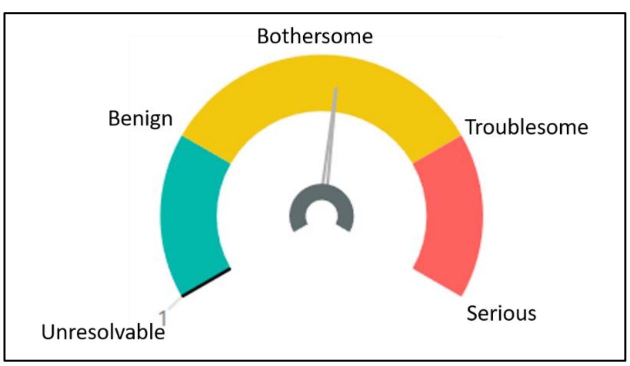



**Figure 4.31: Overall BIM model warnings categorized by impacts. Goal: Below 'Benign'.**

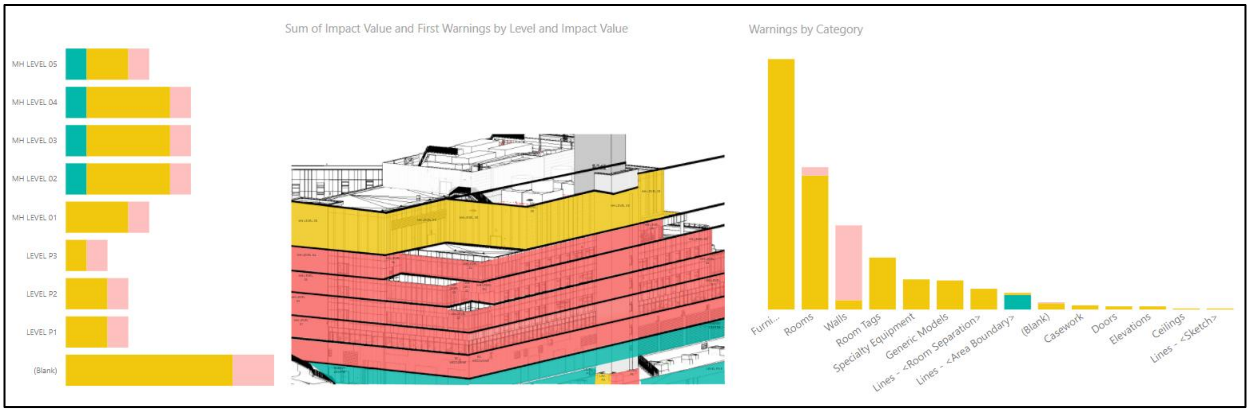



**Figure 4.32: BIM model warnings and its impacts, categorized by [LEFT, CENTER] building levels and [RIGHT] Autodesk Revit categories (like rooms, walls, doors, spaces, etc.)**

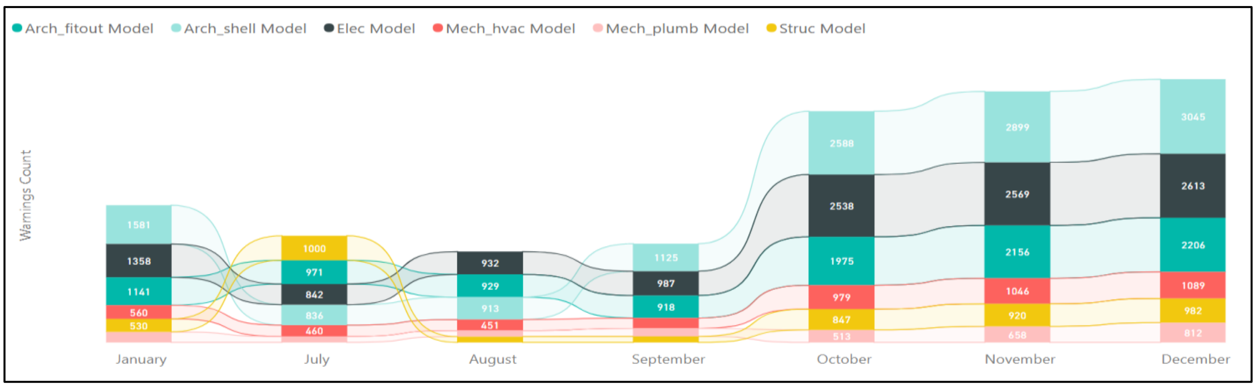



**Figure 4.33: Count of warnings over months, categorized by discipline-specific BIM models**

## 2. Fluctuations in the Model File Size

Although BIM model's file size itself is not an important indicator of the model's performance, significant fluctuations in the file size represent data corruption issues. In a collaborative working models, data corruption can happen unknowingly. Data corruption can be attributable to missing 3D elements, elements with blank or inaccurate information, unreadable data streams, or crash of unsaved models. These data corruptions lead to sudden and significant increment/decrement in the file size. Figure 4.34 shows the graphic used to represent the issue of data corruption.

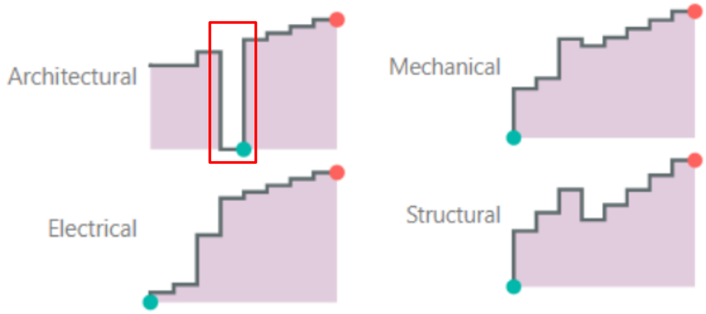



**Figure 4.34: Fluctuations in the file size (in MB) represented on a monthly basis. Red box represents sudden dip in the architectural model's file size thus requiring attention of the architectural BIM lead.**

### 3. Presence of any In-place Families

As per the Owner's BIM standards requirements (BSR), *"Use of in-place families was not allowed. Their use compromises the downstream integrity of the model. Only the use of component and system families was allowed"*. Hence, the presence of any in-place family in the model was notified through the graphics shown in Figure 4.35 and Figure 4.36 below.

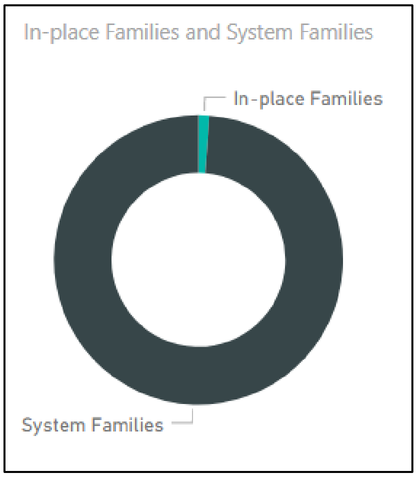



**Figure 4.35: Proportion of in-place families by overall system families. Goal: Zero In-place Families.**

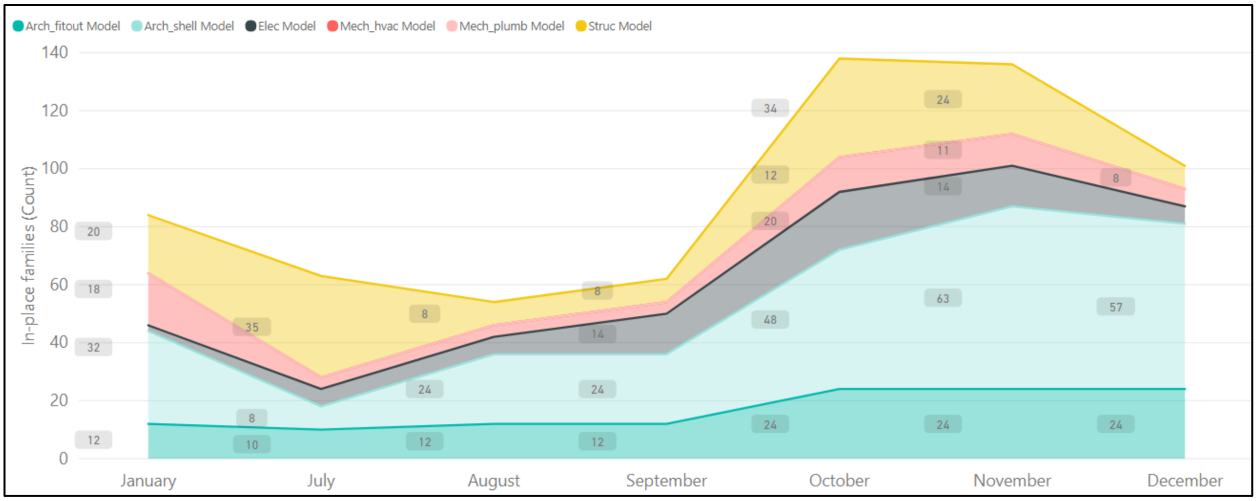



**Figure 4.36: Count of In-place families categorized by BIM models over months. Goal: Zero**

## 4. Presence of Restricted Naming Conventions of Designed Elements

As per BSR, it was to be ensured by the design team that the naming of 3D elements should reflect an easily recognizable description. Construction trades would commission this information later to identify the objects during construction. Thus, use of undescriptive text like “standard”, “PLC”, “default”, “generic”, and consultant’s initials (“stn”) for a family and type name of the element were prohibited. Figure 4.37 shows the graphic used to notify such issue.

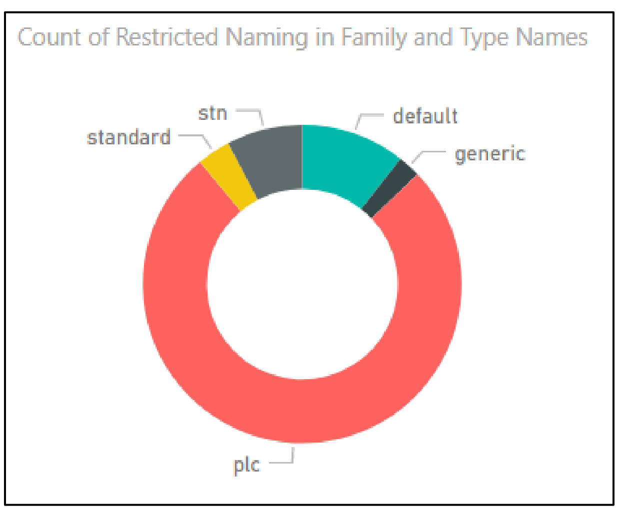



**Figure 4.37: Proportion of restricted terms in the BIM models. Goal: Zero**

### 5. Restricted Objects in the BIM models

BIM Authoring tool, Autodesk Revit, provides a pre-defined classification of objects by object category ('3 x 7 ft single door' in 'doors' category). This built-in structure facilitates consistent graphic and data control of the objects. But in some instances, the tools used to create new objects of certain categories may not provide the flexibility or functionality desired by certain users. Due to this limitation, some users create objects in ways that do not comply with the default structure. Due to this, objects can mistakenly be placed in incorrect categories in the models of different disciplines. Example might include 'floor finishes' as 'ceilings' category placed in structural model, instead of architectural model. This affects the consistency of the graphics and data control of the objects. Figure 4.38 shows the graphic used to notify the team.

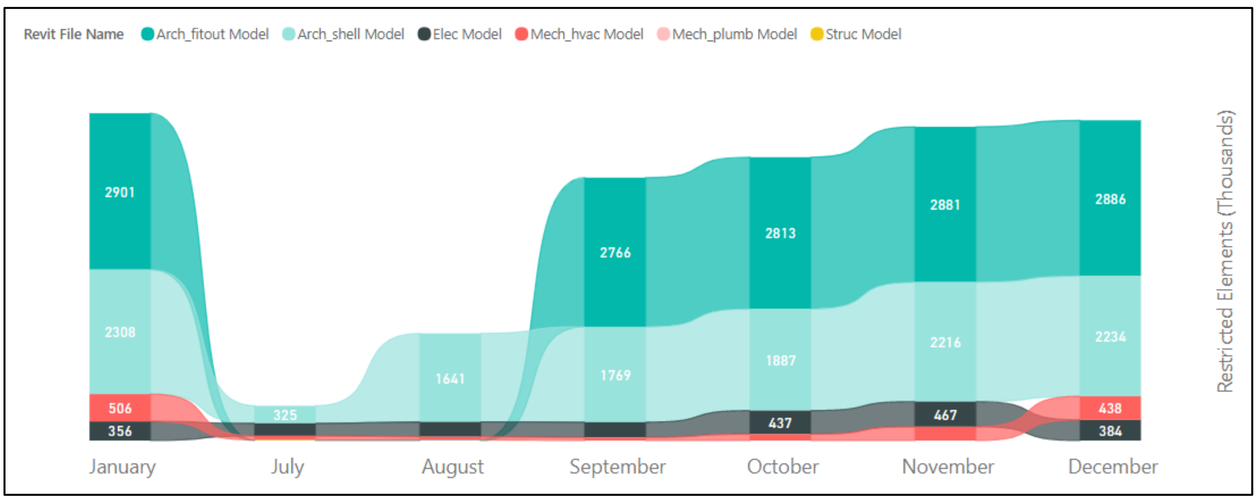



**Figure 4.38: Count of restricted 3D objects in different discipline-specific BIM models. Goal: Zero**

### 6. Schedule of Project Views Not Available on Sheets

Per traditional project workflows, various views (elevations, sections, floor plans, 3D views, etc.) are typically created in large and complex projects. These views are then detailed with a project reference number and printed on drawing sheets, which are further issued to the Owner for reviews and the teams working on the next phase of the project. Per BIM requirements, design team is required to place different project views on the sheets, covering all aspects of the building. On this project, hundreds of views were created to cover all sides and angles of the building for visual quality check reasons. As a result, the duplicate views are required to be deleted and views that the designer forgot to cover needs to be created. This results in a meaningful and cleaner project, and optimum number of views helps in maintaining good file performance. Hence, the views that were not placed on the sheets were notified using the tree-map graphic shown in Figure 4.39 below.

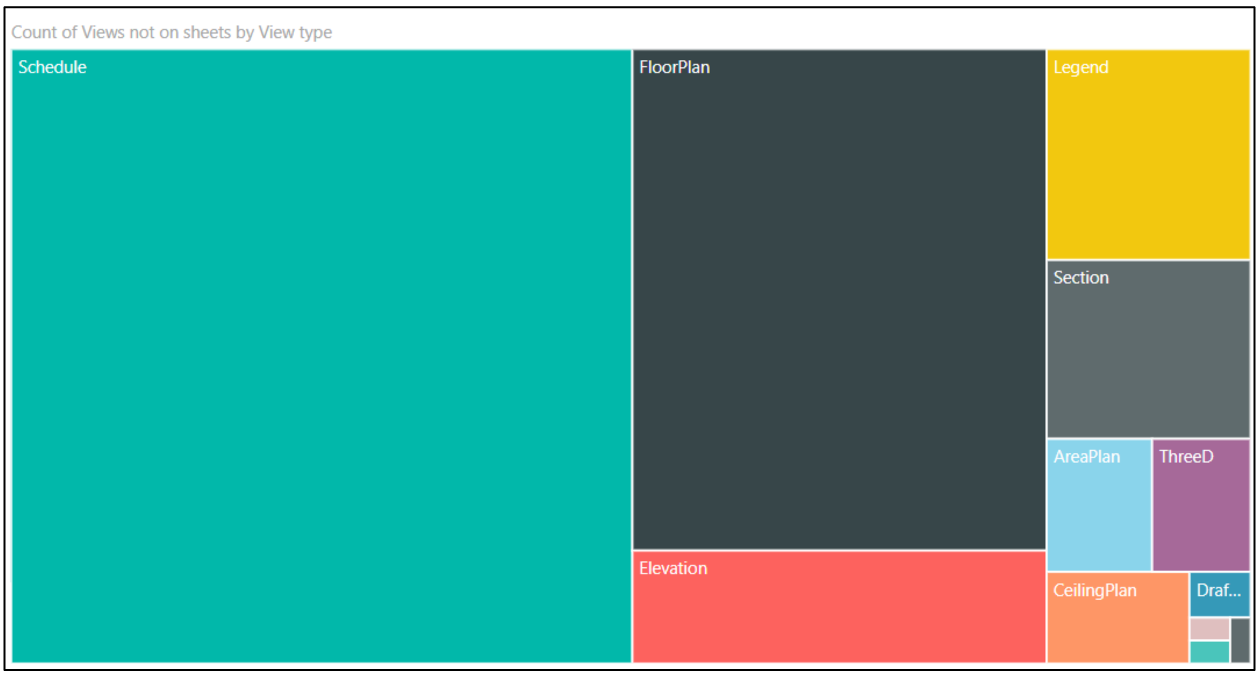



**Figure 4.39: Views not placed on the sheets impacting the significance of the model. Goal: Zero**

## 7. View Templates not available on the Views on Sheets

As per the BIM authoring tool, Autodesk Revit[3], a view template is a "collection of view properties, such as a view scale, discipline, detail level, and visibility settings". View templates are applied to the views that are placed on drawing sheets that needs to be issued to the Owner for visual quality checks. View templates also help in adhering to the company's own standards and attain consistency across construction document sets. Figure 4.40 shows the graphic that was used to notify the team about the views placed on sheets with or without view templates.

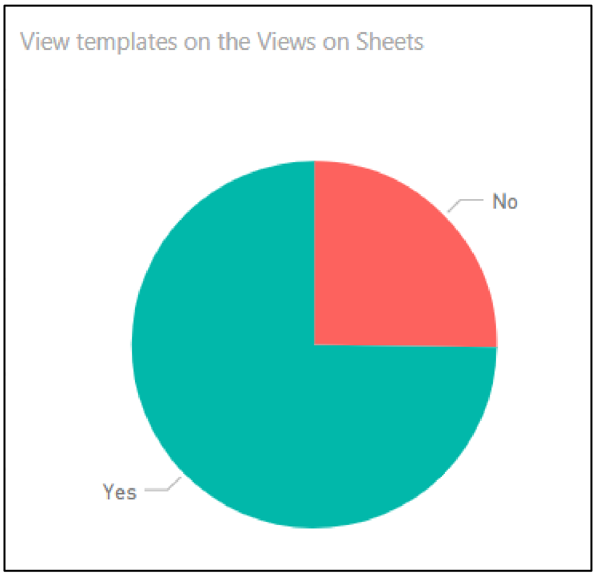



**Figure 4.40: Percentage of views on drawing sheets without the view templates. Goal: Only 'Yes'.**

## 8. Unplaced Model Groups

Model groups are a group of modeled 3D objects/elements that help in maintaining consistency among the repeated objects and streamline design iterations. An example is provided

[3] Autodesk Knowledge Network. View Templates. Retrieved from webpage on July 9, 2018. URL: https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/Revit-Customize/files/GUID-C3B5FB82-3247-48F6-82F0-73011A0F8027-htm.html

in the Figure 4.41.As per the Owner's BIM standards, it was recommended to purge the unused or unplaced model groups. This severely slows down browsing and querying operations in the model, thus affecting the overall performance. Graphic shown in Figure 4.42 below was used to notify the team about the count of model groups over time.

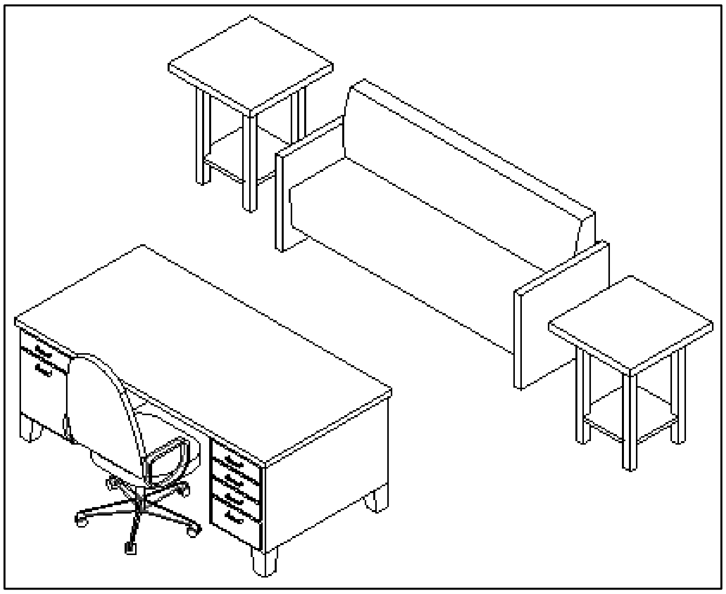


**Figure 4.41: Example of Model Group or a group of 3D objects (Source: Autodesk Knowledge Network, Group of Elements)**

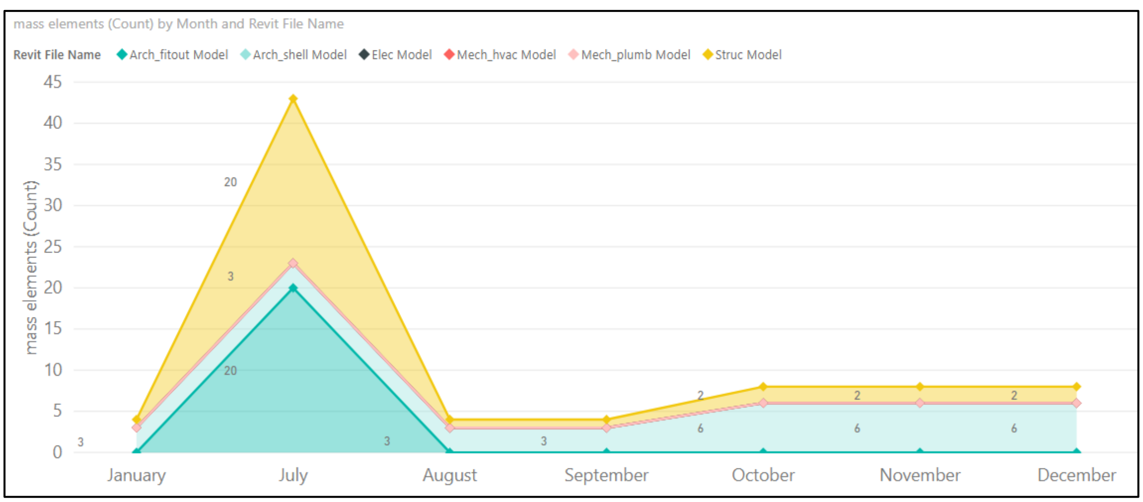



**Figure 4.42: Count of unused model groups over time. Goal: Zero**

### 9. Overall Development of 3D Elements over time

A graphic representing the development of 3D elements in all BIM models over a monthly-basis was provided in the visual report. It was provided to help the team members understand dynamicity of the design process. Compliance is directly dependent on the design elements development. Once the elements are finalized, a check can be run to assess compliance. Stagnant design development graph and almost no development in compliance could be one of the metric that project management team can track to evaluate team's efforts towards compliance with the Owner's requirements. A simple graphic, shown in Figure 4.43 below, was provided.

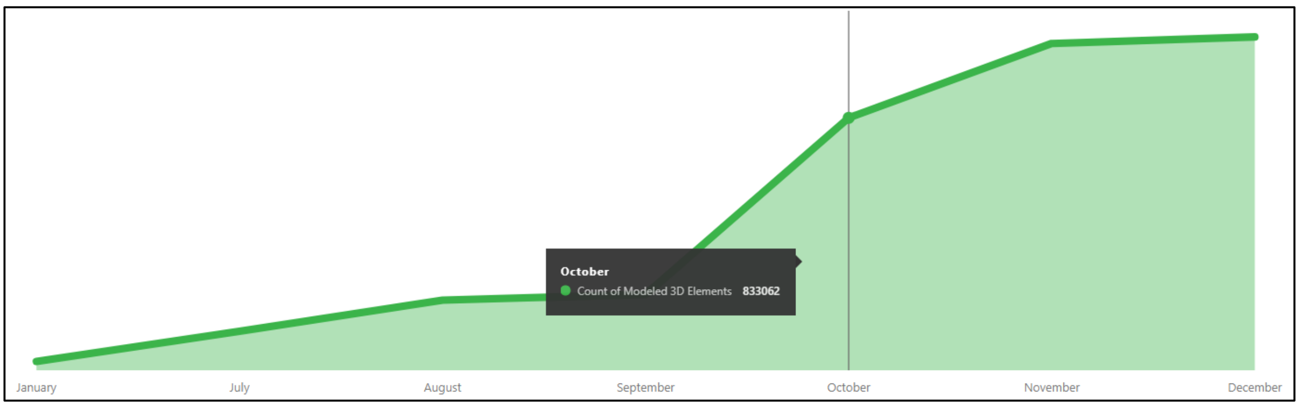



**Figure 4.43: Development in the count of 3D elements in the BIM models. Goal: If count is stagnant, compliance should increase representing continuous efforts from the team to achieve compliance with BIM requirements.**

### 10. Presence of any Unused Elements in the BIM Model

While working on a project, a technician/designer might load more 3D elements (or 3D families like different types of walls, doors, etc.) than required to complete the project. This increases the model's size and can impact the stability of the project. It might also lead to sudden crash when performing intensive operations on the model, like synchronizing the model with project's central server, transfer model to the Owner for audit, etc. Graphic shown in Figure 4.44 was used to represent this metric

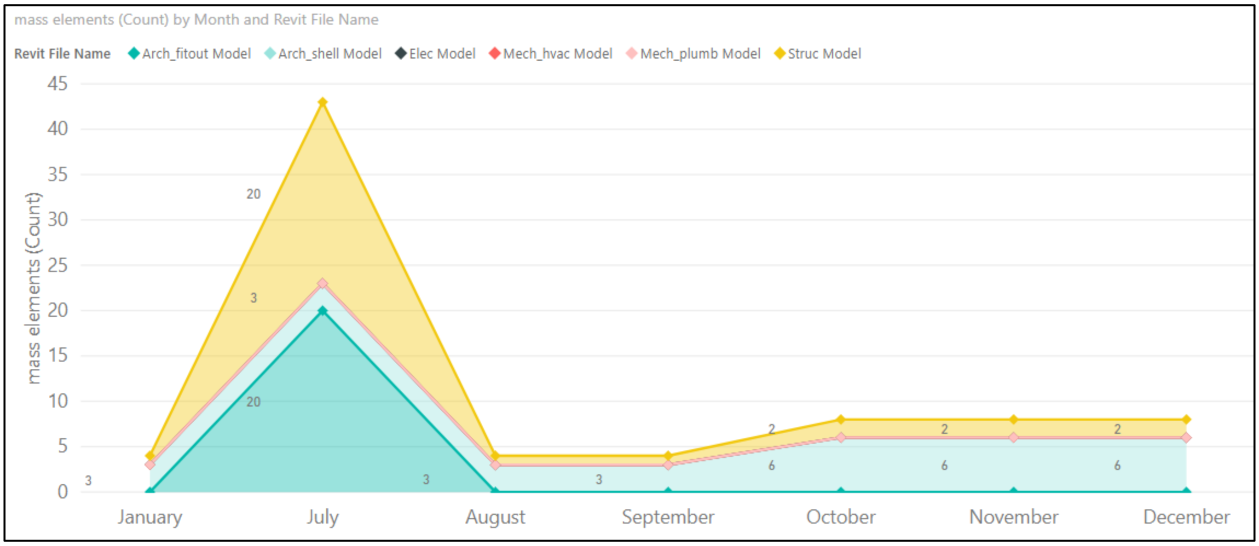



**Figure 4.44: Unused 3D objects to be purged from the BIM model to improve performance. Goal: Zero**

### 4.3.4.2 BIM Information Quality Metrics

**1. Overall Data Completeness Achieved**

To help teams understand the completeness of data parameters explicitly required by the Owner in DGS document to drive construction and operations phase of the project, the following graphic was provided. The growth in compliance (increase in green color) could be tracked through this graphic.

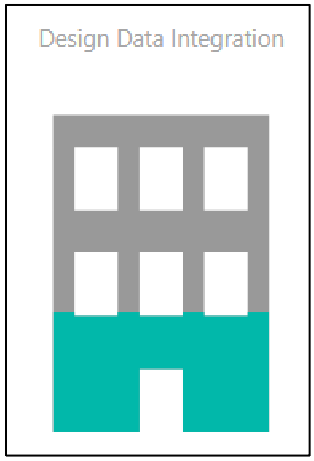
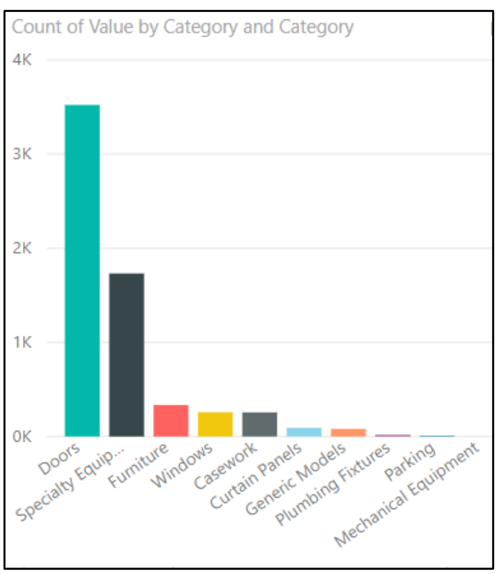



**Figure 4.45: Overall data completeness in the design models, as required in BIM requirements. Goal: 100% (Building filled with green)**

## 2. Data Incompleteness by Categories

Owner's BIM requirements specified the data parametric requirements to drive downstream activities by object categories, like walls, doors, specialty equipment, mechanical equipment, etc. A total of 49 categories were identified and graphics shown in Figure 4.46 below were used.



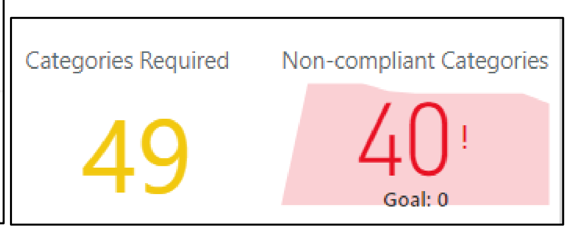




**Figure 4.46: [Left] Count of incomplete data parameters by categories; [Right] Overall non-compliant categories provided on the summary page of the dashboard. Goal: Zero**

### 3. Data Incompleteness by Parameters

The Owner's BIM requirements specified the data parametric requirements to drive downstream activities also by parameter's names, like equipment ID, fire rating value, serial number, omniclass number, access panel required (or not), etc. A total of 236 parameters were identified in the Owner's BIM requirements, and graphics shown in Figure 4.46 below were used.

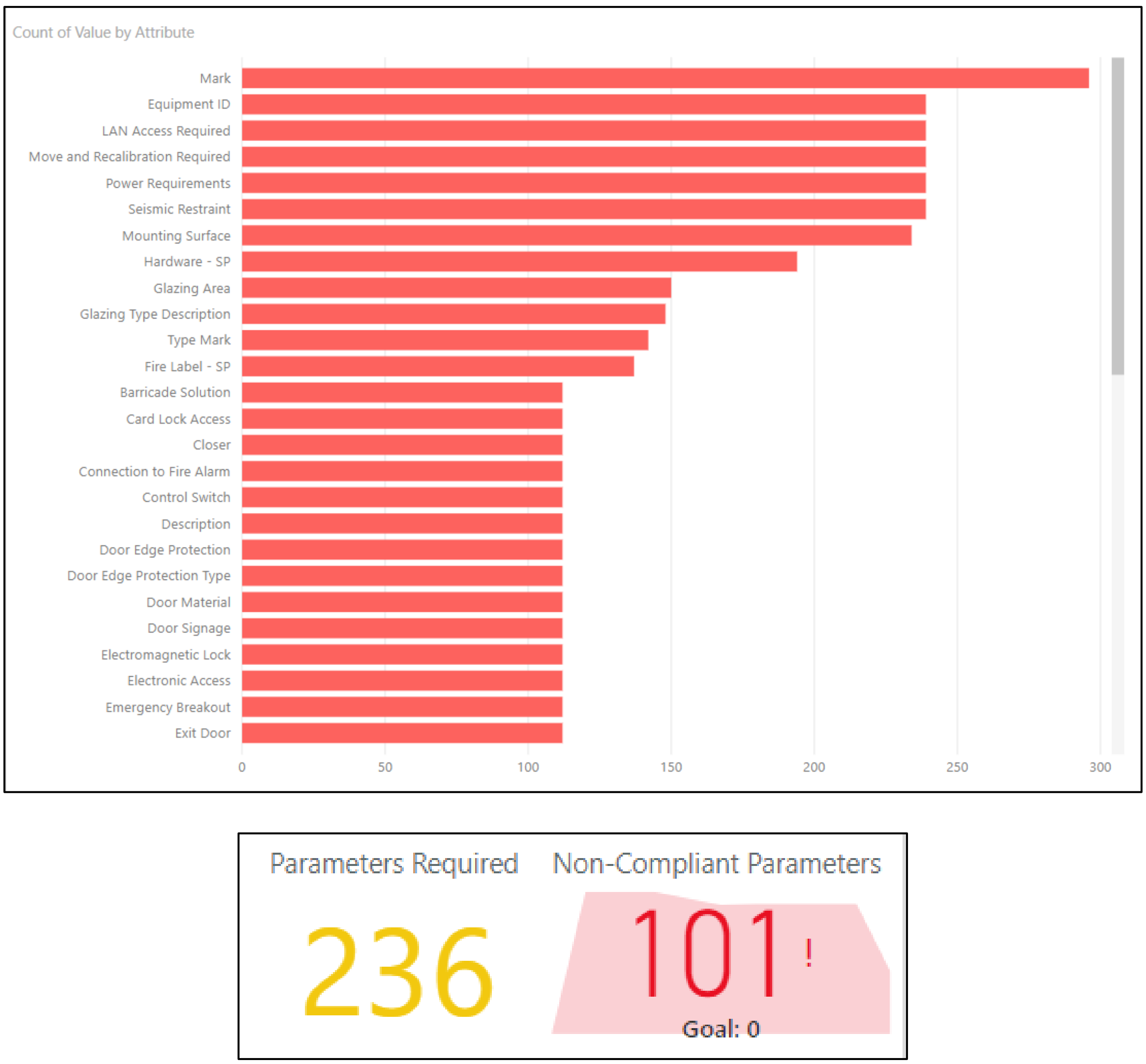



**Figure 4.47: [Top] Count of incomplete (or empty) parametric containers by parameter's name; [Bottom] Overall non-compliant parameters provided on the summary page of the dashboard Goal: Zero**

## 4. Data Quality Reviews

With an idea to provide one platform for the team to conduct all compliance related reviews, a page was provided in the dashboard for the team to conduct quick reviews to assess the quality of data integrated in the BIM models. Filtering functionality was also included for convenience and easy querying. Any inconsistency or inaccuracy observed during this review could then be resolved by the responsible team member. Figure 4.48 shows the page of the report with filters provided on the top for easy querying of information and perform visual checks and Figure 4.49 shows the interactive visualization functionality of the platform for clear understanding about the areas of non-compliance.

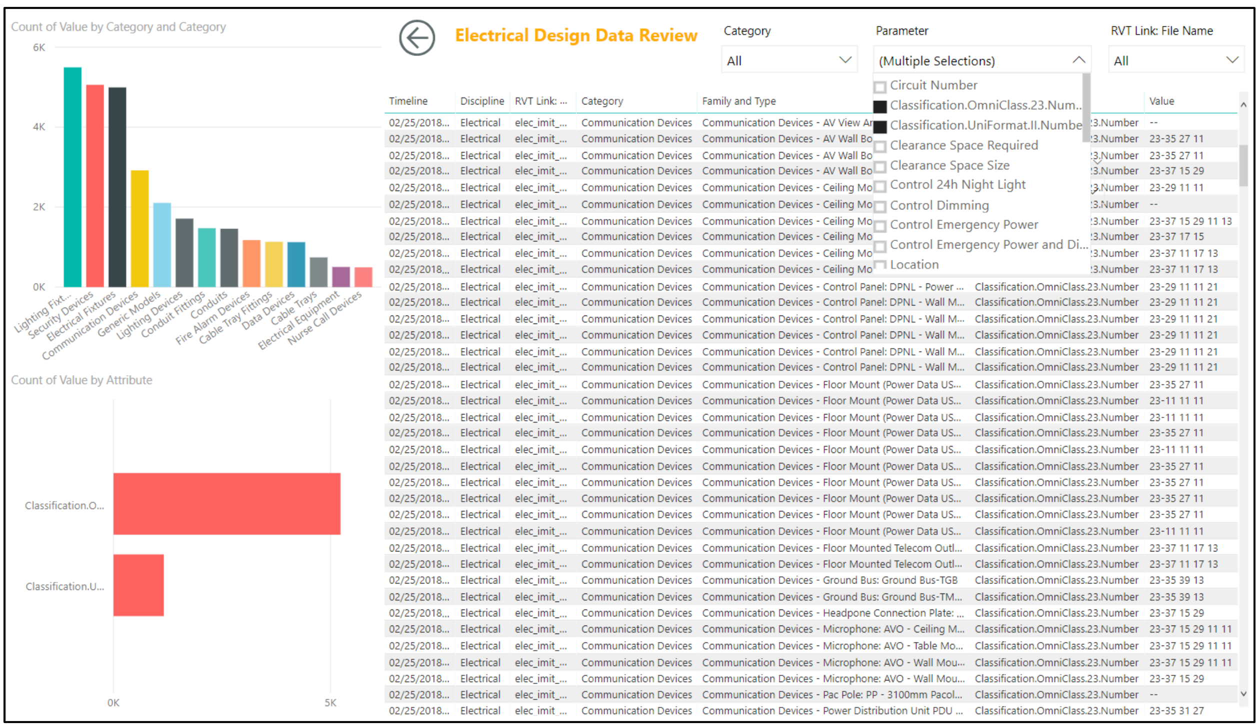



**Figure 4.48: Filtering functionality of the dashboard for compliance-related visual checks**

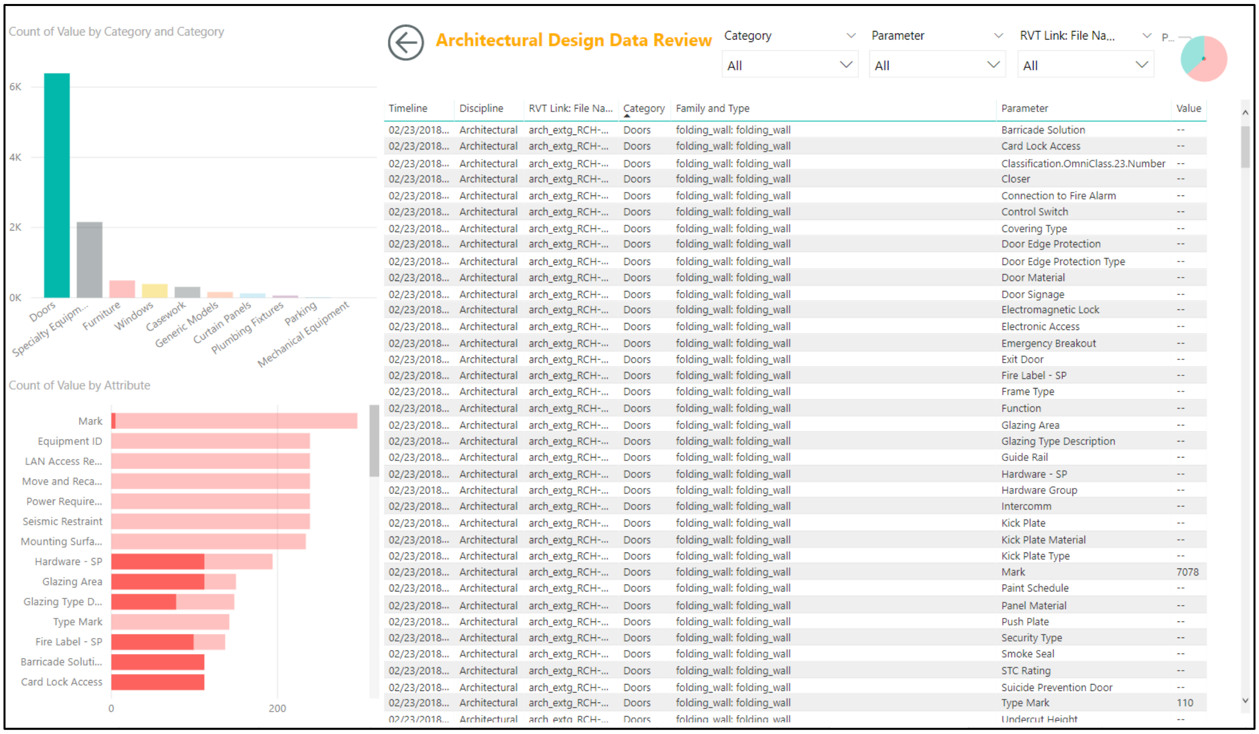



**Figure 4.49: Interactive visualization functionality showing data correlation across different data streams**

### 4.3.4.3 Demonstrating the Dashboard to Understand Consumer Behavior

The dashboard for compliance assessment emerged as a need to help the design team easily perceive the quality of BIM and help the project management team to drive their BIM compliance-related decisions and delegate tasks to the responsible team members. All the graphics created within this visualization platform converted the BIM jargon to "actionable" information and was used to display the key performance metrics for compliance management.

The Author demonstrated the newly developed dashboard to the team, familiarized them with the basic functionality of the interactive visualization platform and how this solution can reduce the technology intensiveness on the project for compliance management. The Author received positive feedback from all the potential consumers of this dashboard. All the inefficiencies observed in the practical motivation of this research were clearly and easily mitigated through this solution. They agreed that this solution has the potential to reduce the complexity in compliance assessment and requires almost no prior training to use the tool and drive decisions. The project manager and provincial BIM lead of the design consultancy urged a need to widen this solution to all the projects across the province with similar BIM requirements.

These dashboards can be leveraged by all the parties involved in the project by using the sharing functionality. It can be shared on the project's server with all the teams and can be accessed on any mobile devices (like laptops, tablets, and mobile phones) at any given time.

### 4.3.5 Specifying the Lessons Learned

At the end of AR cycle 3, an interactive visualization solution was created for the design consultants to assess compliance with the Owner's sophisticated BIM requirements on this large and complex project. This addressed the third objective of this research. Since the design consultants were satisfied with this solution, the Author did not feel the need to pursue another AR cycle. The problems relating compliance, i.e. the model health and information quality, could quickly be identified, tracked and solved over time. Project management could keep a track on the presented metrics and the progress over time. If progress in compliance was not observed through this platform, the project manager could delegate tasks to the responsible teams and support team's efforts to address on-going issues.

# Chapter 5: Conclusions

## 5.1 Summary

The widespread adoption of BIM during design and construction process has induced various complexities in BIM-based project delivery. First, the quality of information integrated to the BIM models is observed to be inaccurate, thus impacting the integrity of BIM and posing risk to the project. Second, inundation of "heterogenous" digital data generated in the BIM environment impacts the team's ability to extract useful insights to inform decisions. Third, the training and support required to get proficient with BIM technologies affects the collaboration and communication among teams. These three complexities are observed to greatly affect the compliance with the Owner's BIM requirements and the overall goal to utilize BIM for downstream purposes. This research addresses these complexities, individually. The three objectives of this research tackle each issue through an action research (AR) methodology. AR is adopted due to its "proactive, practical problem-solving interventionist approach". Thus, a practical problem is solved optimally through three AR cycles, simultaneously creating a theoretical knowledge. Different types of tools are investigated during this research such as Autodesk Revit, Autodesk Model Check Configurator, Autodesk Model Checker, Autodesk Classification Manager, Ideate BIMlink, Autodesk Dynamo, and Microsoft Power BI.

At the end of the first AR cycle, various technologies are identified to check BIM and data compliance in a few minutes, classify BIM data, and manage BIM data for quick quality reviews. A technology-driven BIM compliance workflow was developed with input from an industrial BIM professional to integrate qualitative BIM data to models for compliance. The workflow is further categorized based on the different team's responsibilities. Key process-related and technology-related lessons to streamline the process of compliance were specified in this research.

The second AR cycle was then pursued to reduce the intensiveness and complexities induced by the new technologies identified in AR cycle 1. AR cycle 2 investigates the use of a VPL tool to extract and parse BIM data from the models. The output is presented to the team in simple and easy to understand spreadsheets. BIM compliance-related KPIs were identified during this cycle to extract data reflecting important metrics, making the process leaner and cleaner. The VPL script extracts the required data in a few minutes and requires almost no BIM proficiency.

The third AR was conducted to satisfy design and project management team's need to turn copious amounts of "complex" BIM jargon into actionable information and harness useful insights to drive decisions that scales across all the project teams. An interactive data visualization platform, Viz Dashboard, is developed for the project team that reflects key metrics for achieving compliance with the Owner's BIM requirements. Visualizations need almost no training and support costs.

Therefore, an interactive data visualization platform was created for the project teams to assess compliance and inform compliance-related decision-making. The results of this research helped to simplify the BIM compliance management process for the project and BIM managers, and simplified the BIM health review and data quality assessment process for the designers. Interactive data visualizations build and promote a data culture that empowers every team member and helps them to do their best work with familiar tools to get insights in a fraction of the time.

## 5.2 Process and Technology-related Lessons Learned from Action-Research

The Author noted significantly low progress in achieving compliance with the Owner's BIM requirements during the 'Evaluation' phase of the AR cycles. All the tools and processes can achieve nothing without the support and follow-through with the project teams. All the factors affecting the compliance and the success of BIM compliance process were noted through detailed discussions with the BIM manager, discipline BIM leads and the project manager. These factors are specified here as learnings as the last step of the AR cycle. Discussions were focused on either the process or the technology. Thus, improvements in the following categories were made: (1) process-related improvements, and (2) technology-related improvements.

### 5.2.1 Process-Related Improvements

The Author and the BIM manager created the BIM compliance process on the healthcare project to educate the design team and streamline the process of integrating relevant data to the BIM models. After investigating the right tools and piloting the process, various process-related issues were observed on the project that affected the success of the seeded process. The following process-related improvements were either made by the design team or observed by the Author.

**1. Discuss BIM for FM early on the table with the "right" person**

Suggested by: BIM Manager and Discipline BIM leads

The BIM professionals on the project perceived the requirements as "not feasible" and stated that it is critical to involve the "right" person during early conversations of BIM compliance. They discussed that the traditional way of "people" agreeing on delivering the requirements without considering the core and technical process of design and engineering through BIM needs to be changed. It is critical to involve the facility management team and the BIM professionals from the design and construction stage to create a realistic and feasible set of requirements at an early stage. It can be very beneficial to include the Facility and Asset Manager, who would be the end-user of this enormous amount of information, at the project's conceptualization stage. Facility Managers and operators know what information needs to be tracked to operate buildings efficiently and can help in defining a clear set of BIM for FM requirements at an early stage. This can help optimize the design and build team's data collection and population efforts. The project management teams should also be included to outline a clear set of expectations from the parties involved. Having the appropriate professional early on the table could significantly improve the BIM process's results.

**2. Effective coordination for qualitative data integration**

Suggested by: Discipline BIM Leads

In this project, about 20% of the data and parametric requirements required coordination between different disciplines for accurate data entry to the element in same space in different discipline-based BIM models. For example, the 'Fire Rating' value of the doors in architecture model needs to be coordinated with the hardware in the electrical model. The 'Seismic Restraint' from the structural model needs to be coordinated with electrical and mechanical equipment in the respective models. A better process with the right technologies was required to facilitate high-quality data integration. This could be further improved by incorporating a single BIM model for all the disciplines involved. This way the information generated in the model would be inter-related and well-coordinated.

The project delivery structure might be another factor that was raised by the leads. Having the right delivery structure is pivotal to success. A structure that facilitates a collaborative culture between all the parties involved and harnesses insights of all the teams rather than an authoritarian relationship might lead to better results. For example, a collaborative and results-oriented structure like Integrated Project Delivery (IPD) might be a better choice than Public-Private Partnerships (P3).

### 3. Expecting data compliance at the "right" time

Suggested by: BIM Manager

Inferring from the data and parametric compliance trends recorded over a timeline of 5 months (shown in Figure 4.14), the BIM manager suggested that the Owner should expect BIM data compliance at the "right" time. As per the BIM requirements on this project, the Owner expected complete data compliance during the design development phase. It is imperative to define a 'realistic' timeline for the delivery of FM data requirements. Whatever the project delivery method might be pursued, it is extremely important for the Owner to understand the right time to expect the delivery of information in the BIM Models, to reduce project costs and optimize BIM compliance efforts. The expectation to get the information within the BIM models during and after the completion of design phase can have severe implications on the overall goal of utilizing FM data in the downstream of the project.

Practically, it is not possible to incorporate the FM data during the development of the design models. The design phase of a project is a very dynamic process, and the evolution of the models does not involve a steady increment in the number of modeled elements. Elements are added and deleted from the models in an undefined manner. While working in a collaborative working environment, various placeholder elements are introduced to a BIM model to define spaces in a 3D environment. The design team removes most of these placeholders at final IFC submission stage. Thus, the dynamic nature of the design phase of a project makes it extremely hard to integrate the "right" data to the modeled elements that are finally going to make it to the end. No BIM professional would want to invest efforts in populating information to an unfinalized BIM model, further not representing the as-built conditions of the facility. To mitigate related inefficiencies, it is recommended that the parties involved should resort to a realistic timeline of delivery and effectively manage expectations.

**4. Cultural evolution is pivotal to the success**

Observed by: Author

Ensuring the BIM-FM information is accurate, relevant, and within a scope understood by all stakeholders from the beginning is the key to ensuring the success of BIM in any project. It is therefore critical to forming a collaborative environment in creating BIM information requirements, helping clients to understand what will be useful to their project. BIM is not an end-game or tick-box deliverable, but instead includes all other contractors, and provides hands-on, practical advice from the information requirements throughout project completion. As mentioned previously, the involvement of FM is critical in the early planning and design phase, but this requires a cultural change in the mindset of those involved from functional briefing to commissioning to assess impacts on facilities maintenance and operations costs.

**5. Facilitating talent management through effective recruitment**

Suggested by: Project Manager and BIM Manager

The selection and engagement of a BIM consultant by the Owner to satisfy their desire of using BIM for FM and develop BIM requirements for the project can have far-reaching implications. How the BIM requirements are defined and asked for, in the early stages can greatly affect the project's costs, performance and stakeholder satisfaction. Therefore, it is crucial to not just choose consulting firms by price or qualifications-based selection (QBS), but to look deeper into what is the overall goal of the consulting firm, and how their operations tie into the project's mission and see things the way the facility Owner wants them to.

Professional consulting is a service, and there might be consultants who strongly believe and promote 'BIM for FM', but are primarily involved in the business of selling their CMMS proprietary software. Pursuing similar consultants might lead to a very 'unrealistic' set of BIM requirements. Most of the data collection efforts of the design team could be invested in populating the empty cells within the 3D modeling and CMMS platform, and not focus on what's required by the facility manager to maintain and operate the building efficiently.

Further, an exhaustive set of BIM requirements, dictated by such consultants that just fits into the CMMS software, may not make be understood by the designers, engineers, model managers or BIM managers could result in strain in the collaborative working environment. Therefore, to make the BIM for FM a success, it is pivotal for building Owners to select someone that understands the overall project's mission, develops 'realistic' set of requirements, maintains the right "chemistry", and supports an open and positive working relationship.

**6. BIM requirements to be 'goal-oriented'**

Suggested by: BIM Manager, Architecture BIM Lead, and Mechanical BIM Lead

The BIM Model can capture an infinite amount of design and construction information. The information stored can be useful to show a level of sophistication in the 'BIM for FM' process to the upper-level management and the investors, but most of it might be irrelevant to the facilities maintenance and operations department. Regular maintenance of the stored information can be very difficult and time-intensive to maintain for the project team, as well as the operations staff. Therefore, it is very important to keep the BIM requirements concise. Corresponding to the project's goals, Facility Owners and operators should ask for a clear and simple set of building equipment and system requirements.

This further ties into the quality of information to be provided. More 'realistic' (clear and concise) the information requirements are, the easier it is for the design-build team to populate it right and manage the data. Having enormous lists of what may ultimately be useless information can result in the submission of low-quality data. It would be even harder for the Owner to audit such large volumes of data and consequently, affect the project's overall goal.

### 5.2.2 Technology-Related Improvements

The design team faced issues with the 'new' tools that were identified to streamline the compliance process through automated, rule-based compliance checks, easy information organization, and effective BIM data management. The following improvements were made by the team:

1. **Need for a simple workflow suitable for the entire team**

Suggested by: BIM Manager and BIM leads

As discussed previously, one of the major barriers to BIM adoption is the overwhelming amount of technologies involved in the process. New and intelligent tools were identified by the Author to streamline the process. It turned out that the introduction of these tools induced complexity in the process. BIM leads, designers, and engineers expressed a need to have a simple workflow that is very easy to execute and perceive. Also, the project manager wanted a platform that has very low or almost zero learning curve associated with it.

2. **Simple and automated assessment of compliance with all BIM requirements**

Suggested by: Project Manager

The project manager conveyed to the Author that the compliance reports generated by the intelligent and rule-based model checker are complex to read. The project manager faced difficulty in driving actions from such reports. Also, the compliance reports generated were very inflexible and enormous in nature. The Project Manager expressed a need to have an easy to understand, an executive one-page document that gives an overview of the overall compliance with Owner's BIM requirements.

## 5.3 Summary of Contributions

One of the major challenges that the AECO industry is facing due to the widespread adoption of BIM is to evaluate compliance of the consultants' BIM models to drive the project's downstream operations. If not addressed, non-compliance can greatly affect BIM usage and the project's overall BIM goals. This research adds to the growing body of knowledge in the area of assessing compliance with the BIM requirements. Specifically, four contributions are made in this study.

**Contribution 1:** Development of a technology-enabled BIM compliance workflow for the consultants to integrate qualitative data to the BIM models, in compliance with the Owner's BIM requirements and the company's own BIM standards.

> Various tools were investigated and the ones which can be valuable to the industry for compliance assessment are introduced in this research. A workflow is created to streamline the process of BIM compliance. It is further categorized with the roles and responsibilities of the design, BIM and project management team.
>
> Various process-related and technology-related lessons were learned during this research. They are presented in the last chapter of this thesis for academia and industry to help them understand what can make the process of compliance a success.

**Contribution 2:** Identification of key performance indicator (KPIs) conforming to the BIM model and data compliance.

> BIM model health and IQ KPIs were identified through discussion with the industrial BIM professionals that can be attributable towards assessing BIM compliance on a BIM-based project delivery.

**Contribution 3:** Development of Visual programming script to extract and parse BIM data to reflect the KPIs.

VPL is identified as one of the tools to streamline complex compliance workflows. This tool can be used by BIM professionals with no prior background in computer programming.

**Contribution 4:** Identification of Business Intelligence (BI) tools, Dashboards, as an aid for the project team members to understand their project BIM data and harness useful insights to inform decisions.

Interactive data visualization is used to mitigate communication and collaboration issues faced by the industry professionals, related to BIM compliance. It has the potential to serve as "one version of truth" for all the team members.

### 5.4 Limitations and Future Work

The purpose of this study was to reduce the complexity faced by the AECO industry in assessing compliance with the Owner's BIM requirements through automating data analytics and interactive data visualization. Data reflecting key metrics of compliance are transformed into actionable information to help the project teams harness useful insights to inform decisions. This study is performed on an actual project, a healthcare facility being designed and built in British Columbia, Canada. As the Author was highly involved in the design process of the facility, an action-research methodology was used to intervention the existing practices and develop new workflows. Considering the setting, the research can be deemed to be practically applicable and generalizable to different projects.

BIM compliance can be a very wide term for the AECO industry. This research focused only on the BIM model health and integrated BIM data. Further investigation might be required to expand the scope of the interactive data visualization developed in this research to more compliance-related metrics like coordination issues, system clashes, etc. This research has been conducted only on one project with very sophisticated BIM requirements. Further investigation is needed to ensure the validity for projects with similar and different requirements.

The process and tools developed in this research were developed only for the design consultants on the projects. Other project teams like the Owner’s BIM consultant, general contractor and trades were not involved. To evaluate the wider applicability of this platform, critical teams like the Owner’s organization could also be involved to help them assess compliance with their own requirements.

The interactive data visualization dashboards developed for compliance assessment could not be shared with other project teams due to Microsoft license limitations of the design consultants. Further investigation might be required to evaluate the benefits and impacts of collaboration for compliance assessment using these dashboards.

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