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Quantitative Analysis of Warnings in Building Information Modeling (BIM)

Hyun Woo Lee[1], Hyuntak Oh, AIA[2], Youngchul Kim[3], Kunhee Choi[4]

1 Assistant Professor, School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331, USA, Phone +1 541/737-8539, hw.chris.lee@oregonstate.edu

2 Associate, CO Architects, 5055 Wilshire Boulevard, 9th Floor, Los Angeles, CA 90036, USA, Phone +1 323/525-0500, doh@coarchitects.com (corresponding author)

3 Assistant Professor, Department of Civil and Architectural Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, Phone +852 3442-5432, youngkim@cityu.edu.hk

4 Assistant Professor, Department of Construction Science, Texas A&M University, 3137 TAMU, 429 Langford Bldg A, College Station, TX 77843-3137, USA, Phone +1 979/458-4458, kchoi@tamu.edu

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ABSTRACT

Building Information Modeling (BIM) provides automatic detection of design-related errors by issuing warning messages for potential problems related to model elements. However, if not properly managed, the otherwise useful warning feature of BIM can significantly reduce the speed of model processing and increase the size of models. As the first study of its kind, this study proposes to apply the Pareto analysis to investigate BIM warnings in terms of type and frequency. Based on warning data collected from three California healthcare projects, the analysis revealed that the 15-80 rule applies across the case projects and their design phases—15% of the warning messages are responsible for nearly 80% of the warnings. Two other noteworthy findings include: (1) only the schematic design phase indicates a different Pareto rule of 25-80, as well as warning pattern from other design phases due to its unique purpose; and (2) the decisions of individual design teams are a major variable in the pattern of warning types. Lastly, time estimation for warning corrections is proposed based on learning curve theory to support efficient BIM warning management practices. The results and warning classifications presented in this study are expected to contribute to the design management and modeling practices of design teams involved in large, complex projects.

Keywords: Building Information Modeling; Design Errors; Decision Making; Design Management; Pareto Analysis

HIGHLIGHTS

- The patterns of Building Information Modeling warnings are investigated by applying the Pareto analysis.
- The Pareto analysis reveals that 15% of the warning messages are responsible for 80% of the warnings (15-80 rule).
- The schematic design phase indicates a different Pareto rule of 25-80 as well as a unique warning pattern.
- Time estimation for warning corrections is proposed based on learning curve theory.

1. INTRODUCTION

With more architecture, engineering, and construction (AEC) companies realizing the benefits of Building Information Modeling (BIM) in their projects, its adoption in North America dramatically increased from 28% in 2007 to 71% in 2012 [1]. The AEC industry appears to increasingly agree that BIM has become the critical part of current design and construction practices. The 3D-based virtual models of BIM integrate a vast amount of design information that supports the efficient delivery of capital projects [2]. In particular, BIM can support the reduction of design-related errors and reworks by allowing for automatic detection of errors related to model elements [3, 4]. As a way of error detection, BIM issues real time *warnings* to inform users of potential problems that can harm the key components of design information, such as the integrity of the model, the design intent, and the reliability of documentation [5].

One unique nature of BIM warnings is that users are allowed to dismiss warning messages when issued. Warnings then are stored and maintained by the BIM system until users revisit them at their convenience. When users wish to make corrective actions, the system allows for a quick retrieval of previously dismissed warnings. In a large, complex project, it is common to see warnings accumulate into the thousands. Because BIM is processor-intensive and requires a high level of computing, such excessive warnings are known to significantly reduce the speed of model processing and increase file sizes [6]. Therefore, users are required to diligently manage the accumulating warnings in order to prevent this useful feature from causing inefficiency during the design and modeling processes.

However, despite the significance of BIM warnings, there has been little to no research aimed at investigating them. In response, the overarching goal of this study is to describe and analyze warning data by applying the Pareto analysis. For the purpose of this study, a total of 15,586 warning messages were collected from three California healthcare projects of varying types and sizes, where Autodesk Revit® was used as their main BIM software.

Based on the extensive literature review, this study is found to be the first of its kind that attempts to classify and analyze BIM warnings. Although we make no attempt to generalize the results of this study to the rest of the BIM community, the rigor of this study can be seen as a step forward in providing insight regarding patterns and classifications of BIM warnings. The findings and proposed classifications are expected to contribute to the design management and modeling practices of the AEC industry, especially for design teams involved in large, complex projects.

2. BACKGROUND

This section summarizes the literature review that was performed in various subject areas including BIM, design errors, and the Pareto analysis.

2.1 BUILDING INFORMATION MODELING (BIM)

Information technology (IT) supports the development of projects in an efficient manner while streamlining the different phases of construction [7]. As a recent IT innovation in virtual design and construction (VDC), BIM provides a new approach to design, construction, and facility management by enabling the 3D-based representation of design information, improving project and design coordination accordingly [2]. In recent years, BIM has been widely used for many different activities during the project lifecycle including building design, structural design, equipment management, cost estimation, and property management. A survey about BIM usage [8] showed that BIM is most frequently used during the design stage (55%), followed by the detail design and tender stage (52%), construction stage (35%), feasibility stage (27%), and operation and maintenance stage (9%).

A number of studies have reported benefits from the implementation of BIM in construction projects [9, 10]. BIM provides an integrated platform of building design for energy efficiency

[11], and supports construction and project managements [12, 13]. Overall productivity can be improved because BIM helps to improve the coordination and communication of design information by sharing a centralized model with the other project members [14]. Using BIM enables a greater exchange of information between the stakeholders, designers, manufacturers, and contractors. It also improves the quality of the information, which accordingly allows for informed decision making [15].

Due to its collaborative nature, BIM requires an enhanced collaboration among project parties, which leads to unique challenges in terms of standards [16], interoperability [17], systems integration [18], collaboration [19], and change management [20]. Also, how to define the responsibility of project parties is also a concern, because BIM allows various project members to simultaneously participate in modeling [21]. Hence, the collaborative nature of BIM modeling requires enhanced design coordination amongst design team members. In particular, warning management must be part of design coordination practices, because BIM warnings intend to alert users of errors and issues in modeling. Through real time warning messages, BIM allows for automatic detection of design errors, supplementing the human cognition process in error detection.

2.2 DESIGN ERRORS AND ERROR CLASSIFICATIONS

Human error can be divided into two levels of human cognitive performance based on whether mistakes occur either in a previously experienced situation or in a new one [22, 23]. Regarding the level of human cognitive performance, Rasmussen [22] classified those errors into one of three categories: skill-based slips (or lapses) that occur unintentionally during familiar routine, rule-based mistakes that occur in previously experienced situations, and knowledge-based mistakes that occur in new situations when using similar experiences from a similar situation. Because mistakes are the consequence of inappropriate planning and decision-making, it is more difficult to detect mistakes in advance than it is to detect slips (or lapses) [24].

In that regard, architectural design errors occur in two representative situations: miscommunications between various parties in a project, and cognitive limitation when considering too much data and information simultaneously [24]. Errors made during the design process (such as modeling errors in BIM) can either be slips of unintentional occurrences because of cognitive limitations in regular routines such as drawing plans and writing documents, or mistakes from inappropriate planning and decision-making when solving spatial problems or choosing systems.

While slips are more noticeable, architectural design mistakes are hardly detected as errors unless they become noticeable errors at a certain stage of designing. Because the architectural process continues to progress, unless the design mistakes are implemented, they will not be realized as errors in the final product/model [25]. However, architectural design slips may be noticeable at the beginning because they can easily be identified as different or inappropriate in common routines. Assigning different groups to multiple checkpoints where they utilized their field experience and theoretical backgrounds during the design process appeared to reduce design error in architectural projects [24]. Although errors occur at both design and production phases of architectural design, errors at the latter stage cost more financially and in terms of effort to recover [25].

Similarly, Lopez et al.'s error taxonomy that was based on human cognitive performance illustrates that design errors were divided into three categories: skill- or performance-based errors, which were associated with slips of incautious performance in accustomed routines; rule- or knowledge-based errors, which were associated with mistakes; and intentional violations or noncompliance, which were a refusal of appropriate actions [26]. Based on the error taxonomy, design errors were classified with the levels of design errors, which are personal, organizational, and project levels [26]. Similarly, Busby [27] divided the cases of errors in design process into five elements: participants, designs, tools, organization, and environment. Among the 75 cases of error, participants turned out to be the largest source of error, which caused 27 cases (36%), followed by design (25%) and organization (25%), tools (7%), and environment (7%).

Although a number of studies investigated design errors and their classifications during design process, there have been few studies aimed at investigating BIM errors. To fill the gap, the present study seeks to apply the Pareto analysis in order to investigate BIM warnings.

2.3 PARETO ANALYSIS IN SOFTWARE ENGINEERING

The Pareto principle, also known as the 20-80 rule, was introduced by the Italian economist Vilfred Pareto when he found that 20% of people owned 80% of wealth in Italy. The principle is universally applied to a number of different domains—including economics, business, engineering, and quality control—in order to signify "vital few and trivial many" [28].

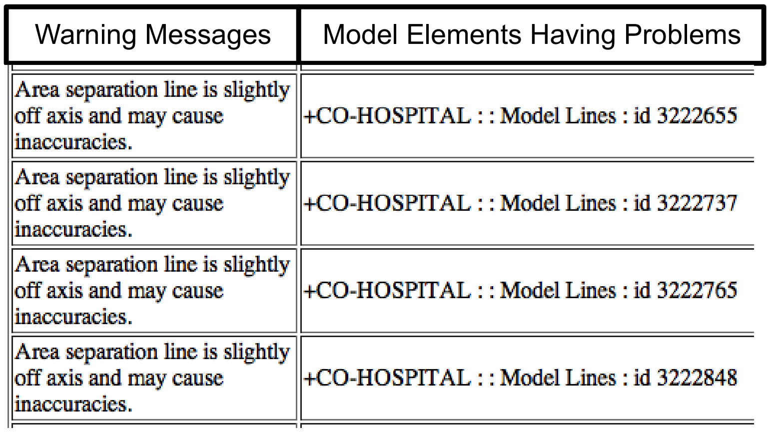
In particular, a number of studies in software engineering applied the Pareto principle in order to categorize and quantify the frequencies of different types of errors, faults, and failures during software development. Most studies aimed at validating a common belief that most issues result from a small number of causes. For example, Fenton and Ohlsson [29] found strong evidence that 20% of the modules contained nearly 60% of the faults (20-60) and 10% of the modules lead to 100% of the failures (10-100). Similarly, later studies confirmed the Pareto principle in software engineering—that 80% of all errors were caused by either 20% of all bugs detected [30] or 20% of codes [31].

3. RESEARCH OBJECTIVES AND METHODS

This study has three objectives: (1) to empirically test a hypothesis that a small number of warning messages contain most warnings (the Pareto principle); (2) to identify meaningful warning patterns across projects and design phases; and (3) to develop time estimation for correcting warnings. The following shows the research process as implemented in the study, in order to achieve the intended objectives:

1. Collect BIM warning data from case projects.
2. Determine the classifications of warnings based on feedback from project designers.
3. Sort warning messages based on their frequencies.
4. Test a hypothesis of the Pareto principle.
5. Infer different patterns of warnings in terms of projects and design phases.
6. Determine the reasons for the identified patterns through follow-up interviews with the designers.
7. Develop time estimation for warning corrections

To better understand the context of BIM warnings, it is important to differentiate *warning messages* from *warnings*. In the present study, "warning messages" refers to the messages that are universally pre-defined by a BIM provider (e.g., Autodesk for Revit) while "warnings" refers to the individual warnings that are specific to each model. This means that when there is an issue with a model element, BIM issues a *generic* warning message that is specifically linked to that element. Accordingly, warnings are sorted by each warning message in the warning dialog box or warning reports, and each message likely pertains to multiple warnings for different model elements of BIM, as shown in Fig. 1.



Warning Messages	Model Elements Having Problems
Area separation line is slightly off axis and may cause inaccuracies.	+CO-HOSPITAL : : Model Lines : id 3222655
Area separation line is slightly off axis and may cause inaccuracies.	+CO-HOSPITAL : : Model Lines : id 3222737
Area separation line is slightly off axis and may cause inaccuracies.	+CO-HOSPITAL : : Model Lines : id 3222765
Area separation line is slightly off axis and may cause inaccuracies.	+CO-HOSPITAL : : Model Lines : id 3222848

Fig. 1. BIM warning report showing warning messages and corresponding model elements (screenshot courtesy of CO Architects)

4. DESCRIPTION OF CASE PROJECTS

For the purpose of this study, a total of 15,586 warnings (based on 53 warning messages) were collected from three California healthcare projects. This section provides brief descriptions of each project.

4.1 PROJECT K

Project K was to provide a new acute care hospital in San Diego, California. When complete, this 51,100-m^2 hospital would house 321 beds in three patient towers that are seven-stories plus a basement level. The project was delivered by construction management at risk (CM at risk) that promoted the use of BIM and facilitated active communication between the client, the design team, and the contractor from the very early stage of the project. The design process started in 2011 and completed in 2013. The construction started in March 2014.

4.2 PROJECT P

Project P was to build a new 360-bed acute care hospital located in Escondido, California. The building spans a gross area of 69,000-m^2 with 11-stories and a basement. The project started in 2005, and the design and agent approval process lasted for 4 years. The construction was completed in 2012. Project P was one of the very first large scale healthcare projects that extensively implemented BIM. During the schematic design (SD) phase, AutoCAD Architecture [formerly known as Architectural Desktop (ADT)] was used for design and documentation. However, from the design development (DD) phase to the end of the construction document (CD) phase, Revit was used as the main BIM software. As a result, Project P did not have warning messages for the SD phase. Another unique element of Project P was that it was delivered via Integrated Project Delivery (IPD), an alternative project delivery that promotes team collaboration, multiparty contracting, and sharing of risk and reward [32]. The collaborative environment allowed for the active use of BIM for design, documentation, presentation, and coordination from the very early stage of the project.

4.3 PROJECT Q

Project Q was to add a new 6,700-m^2 pavilion to the existing hospital. The two-story-plus-basement building is located in Napa, California and includes 20-bed intensive care units, "Smart and Hybrid" operating rooms, and supporting facilities. Because it was small in its project size, the design team did not separate their BIM into several pieces, as is typically required for a large project. Instead, one model centrally contained all the architectural 3D elements, which significantly increased the coordination efficiency, and reduced potential clashes among multiple models. In addition, the application of an alternative project delivery, called a BIM-enabled lean delivery process, helped maximize the effectiveness of BIM as the primary method of communication and coordination. The design and permit process of Project Q lasted for two years, and its construction was completed in 2013.

5. CLASSIFICATIONS OF WARNING MESSAGES

Based on collective feedback from a group of architects that were involved in the three projects, warning messages were first classified by three types: annotation, information, and geometry. Then, the geometry warnings were further broken down into four sub-types, such as duplication, system, conflict, and miscellaneous, because they account for 51% of the total counts. Table 1 summarizes the shares of each warning type. The number of warnings per unit gross area of building (warnings per m^2) ranges from 0.08 to 0.14, with an average of 0.13.

Table 1. Warnings by types and projects

Warning Types		Warning Messages		Project K		Project P		Project Q		Total	
		Count	Share	Count	Share	Count	Share	Count	Share	Count	Share
Annotation		3	5.7%	573	3.7%	2390	15.3%	205	1.3%	3168	20.3%
Information		4	7.5%	3229	20.7%	1196	7.7%	89	0.6%	4514	29.0%
Geometry	Duplication	9	17.0%	2319	14.9%	2715	17.4%	176	1.1%	5210	33.4%
	System	13	24.5%	209	1.3%	1223	7.8%	1	0.0%	1433	9.2%
	Conflict	4	7.5%	112	0.7%	57	0.4%	45	0.3%	214	1.4%
	MISC	20	37.7%	494	3.2%	509	3.3%	44	0.3%	1047	6.7%
Total		53	100.0%	6936	44.5%	8090	51.9%	560	3.6%	15586	100.0%
Warnings per unit area of building (warnings/m^2)				0.14		0.12		0.08		0.13	

Geometry-duplication is the most frequent warning source (34%), followed by information (29%), annotation (20%), geometry-system (9%), geometry-MISC (7%), and geometry-conflict (1%). Geometry-duplication, information, and annotation account for 83% of the total warnings, although the three types pertain to only 16 messages out of 53.

In addition, to support effective development of time estimation for warning corrections, the study employed additional classification based on priority levels of warning messages, as follows:

- High priority: Warnings that have a significant impact on the quality of models and documentation, and hence must be resolved immediately.
- Medium priority: Warnings that do not have an immediate impact, and hence can be resolved later.
- Low priority: Warnings that have little to no impact, and hence do not need to be resolved unless requested otherwise.

5.1 ANNOTATION WARNINGS

Annotation is a 2D element that is added to provide additional information about a 3D element. Text notes, room tags, door tags, callouts, and keynotes are all annotation. BIM produces annotation warnings when the association of an annotation with a 3D element is broken. This often occurs when an information tag is misplaced. If this happens within a working view of BIM, it is regarded as a warning of low priority. However, if it takes place within a view that is part of contract documents, annotation warnings become critical because it may lead to an incorrect interpretation of the documents. Accordingly, they are classified as warnings of high priority and must be addressed immediately (see Example B of Fig. 2). Fig. 2 presents two representative examples of annotation warnings.

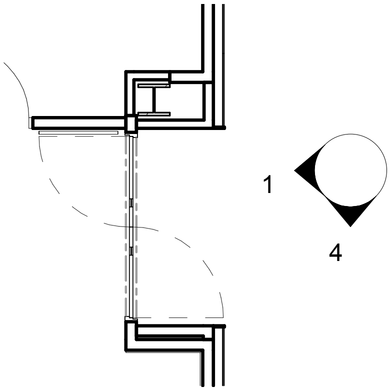
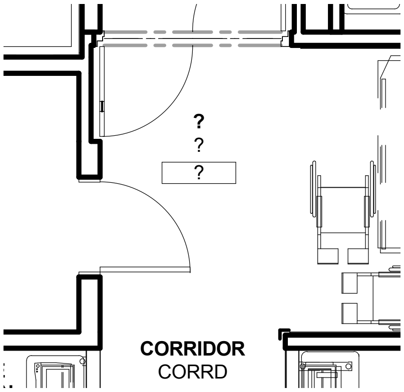
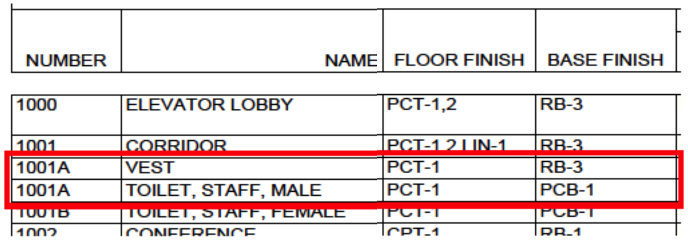
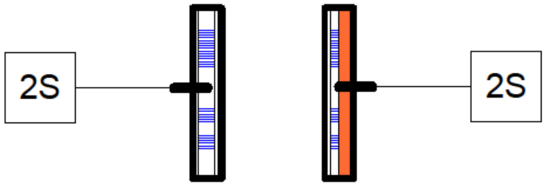
	Example A	Example B
Warning Messages	*An elevation symbol references views on more than one sheet. It will show a blank sheet reference. To show the correct references, use a separate elevation symbol for the views on each sheet.*	*Room Tag is outside of its Room. Enable Leader or move Room Tag within its Room.*
Priorities	High priority	Medium priority
Screenshots		
Descriptions	Two elevations were created from one elevation bubble that was placed on two different sheets. This resulted in a blank bubble where a sheet number is supposed to appear. This problem is not limited to one view but project wide, and can lead to confusion during construction.	The room tag is showing question marks because it was placed outside of its room boundary. If this happens within a working view, it is ignorable. If this happens within a contract drawing, it will cause confusion.

Fig. 2. Examples of annotation warnings (screenshots courtesy of CO Architects)

5.2 INFORMATION WARNINGS

Information warnings are intended to warn users about potential conflicts among the information embedded in elements such as wall types or door/window numbers. Some types of information warnings are of high priority. For example, duplicate information of door numbers or types in construction documents will cause confusion potentially leading to a problem during construction (see Example C of Fig. 3). However, it is important to note that some design teams intentionally let information warnings happen depending on the team's practices. For instance, if a designer wants to display two different graphic styles for one type of wall, he/she may intentionally create two types of wall and give them the identical name (see Example D of Fig. 3). By doing so, the user would get information warnings that are intentional and can be ignored accordingly. This practice will be discussed in a later section with a case. Fig. 3 presents two representative examples of information warnings.

	Example C	Example D
Warning Messages	*Elements have duplicate 'Number' values.*	*Elements have duplicate 'Type Mark' values.*
Priorities	High Priority	Medium Priority
Screenshots		
Descriptions	Two rooms have an identical room number. Most room coordination is made possible by using room numbers. Thus, this can create issues during construction.	These two walls have the same structure but serve different purposes. To differentiate these two graphically, the design team decided to create two types of walls, but gave them an identical type mark.

NUMBER	NAME	FLOOR FINISH	BASE FINISH
1000	ELEVATOR LOBBY	PCT-1,2	RB-3
1001	CORRIDOR	PCT-1,2 LIN-1	RB-3
1001A	VEST	PCT-1	RB-3
1001A	TOILET, STAFF, MALE	PCT-1	PCB-1
1001B	TOILET, STAFF, FEMALE	PCT-1	PCB-1
1002	CONFERENCE	CPT-1	RB-1

Fig. 3. Examples of information warnings (screenshots courtesy of CO Architects)

5.3 GEOMETRY WARNINGS

BIM alerts users with geometry warnings when physical clashes between 3D elements occur. For example, if two equivalent kinds of elements are overlapping, or if a wall is meeting another wall where a wall opening is located, a geometry warning is issued. These “cannot-occur-in-the-real-world” issues are important to address, though the priority levels of geometry warnings may vary. For instance, if a wall is overlapping with a room separation line, a warning is created. However, since room separation lines are not real 3D objects that define spaces, this warning can be of low priority (see Example G of Fig. 4). However, if a wall is perpendicularly conjoining a window (see Example E of Fig. 4), the warning represents a serious problem that needs to be fixed immediately. When it comes to geometry warnings, priority levels of a warning can also vary depending on the purpose of modeling. If the model is used only for document printing, duplication can be ignored as long as it does not create a graphical error (see Example F of Fig. 4). However, if the model is to be used for quantity takeoffs, geometry-duplication warnings have to be resolved immediately in order to prevent any quantity discrepancies. Fig. 4 presents three representative examples of geometry warnings.

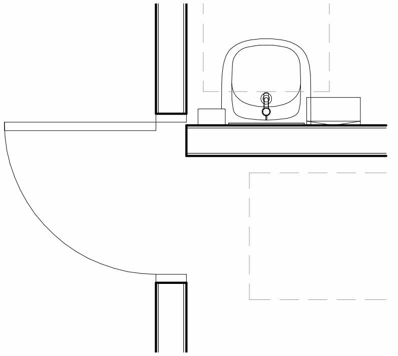
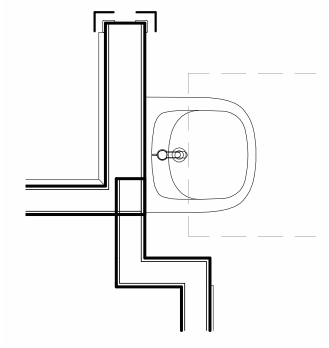
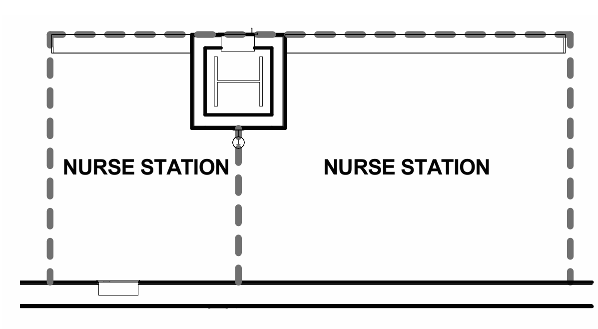
	Example E	Example F	Example G
Warning Messages	*Insert conflicts with joined wall.*	*Highlighted walls overlap. One of them may be ignored when Revit finds room boundaries. Use Cut Geometry to embed one wall within the other.*	*A wall and a room separation line overlap. One of them may be ignored when Revit finds room boundaries. Shorten or delete the room separation line to remove the overlap.*
Types	Geometry-conflict	Geometry-duplication	Geometry-duplication
Priorities	High priority	Medium priority	Low priority
Screenshots			
Descriptions	A wall joins at a door opening. This should not happen in construction, and has to be addressed immediately.	Two walls overlap. This is a common drafting mistake. Even though they do not directly affect construction, this mistake appears on the drawings, and needs to be fixed.	A room separation line (dashed line) overlaps with a wall. This can be ignored because this affects neither the drawing nor the model.

Fig. 4. Examples of geometry warnings (screenshots courtesy of CO Architects)

As stated earlier, this study further categorizes geometry warnings into four sub-types, as follows:

- Geometry-duplication: Warnings that are issued when two or more model elements overlap.
- Geometry-conflict: Warnings that are issued when void elements conflict with solid elements.
- Geometry-system: Warnings that are issued when the inaccuracy of model elements cause system issues.
- Geometry-MISC: Warnings that are not part of the other three sub-types.

The following section presents the result of the Pareto analysis that was performed at project and design phase levels. The main objective was to empirically test a hypothesis that a small number of warning messages represent most of the warnings generated during the BIM design development process.

6. PARETO ANALYSIS OF BIM WARNINGS

Fig. 5 illustrates that about 15% of the warning messages are responsible for nearly 80% of the warnings (15-80 rule). This finding is in alignment with the Pareto principle observed in software engineering studies that found a small number of the modules or codes led to the majority of the faults or errors.

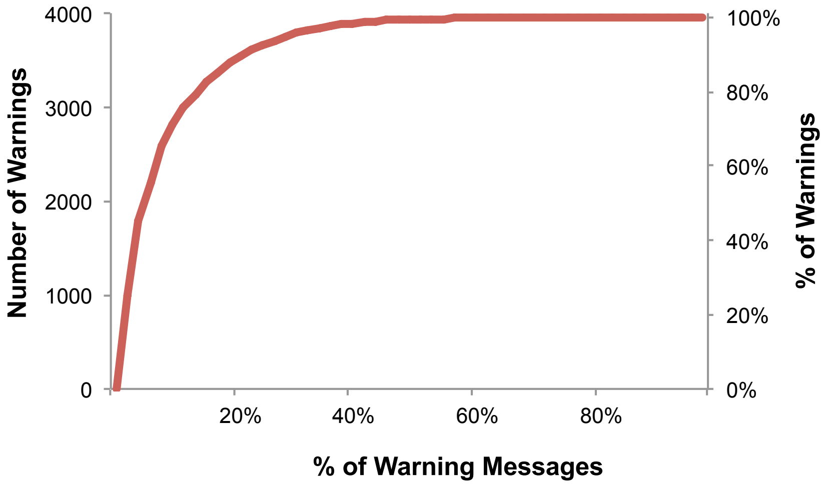


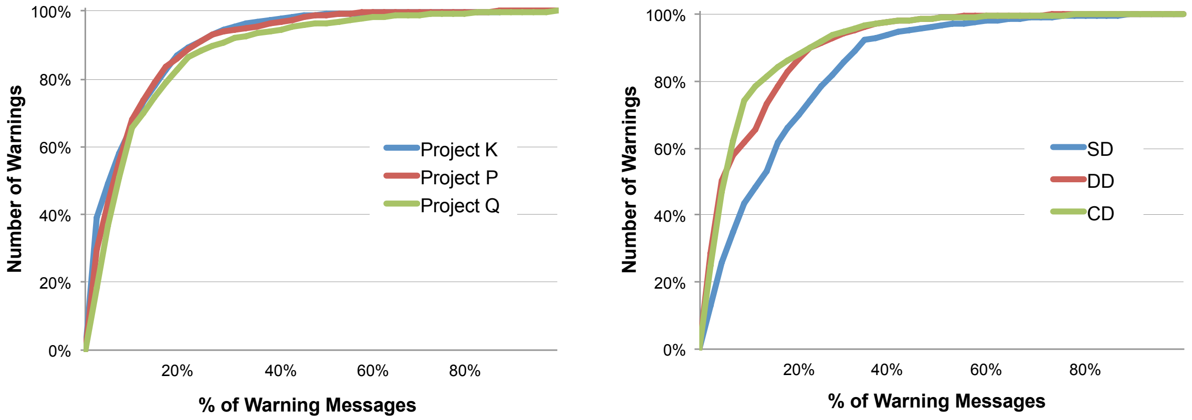
Fig. 5. Pareto diagram of warnings from three California healthcare projects

Despite their differences in project size, type, and delivery method, an almost identical 15-80 rule is found when warnings are arranged either by project [Fig. 6(a)] or design phase [Fig. 6(b)], except for the SD phase indicating that 25% of the warning messages are responsible for nearly 80% of the warnings (25-80 rule). Based on follow-up interviews with the architects of CO Architects, the difference appears to be due to the following uniqueness of the SD phase:

1. Designers focus more on producing various design schemes than making warning-free models. As a result, numerous types of warnings are ignored.
2. Multiple design options are simultaneously carried inside one model, which leads to

ignorable warnings.

3. Clients require a quick turnaround from SD, which does not allow enough time for designers to deal with warnings.
4. Models are typically small and warnings do not necessarily slow down the processing time.



(a) Arranged by projects

(b) Arranged by design phases

Fig. 6. Pareto diagram of warnings by projects (a) and by design phases (b)

7. ANALYSIS OF WARNING TYPES

The shares of six warning types are analyzed by each project and presented in Fig. 7. Two noteworthy findings across the projects are:

- Annotation warnings account for 30% and 37% of warnings from Projects P and Q, respectively, while they only account for 8% in Project K.
- 47% of warnings from Project K are related to information warnings, which is over three times more than in Projects P or Q.

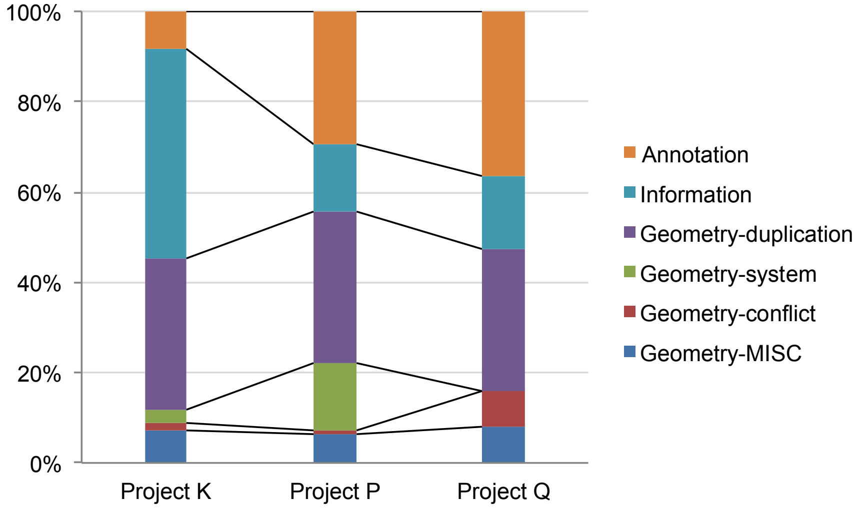


Fig. 7. Warning types by projects

Interviews with designers that were involved in Project K revealed that the design team arbitrarily decided to have an identical type number for different types of walls. For example, there were two types of walls in Project K; their structures were identical, but the designated functions were different. In order to differentiate them on the floor plan, the design team created two wall types with different graphic appearance and gave them the same type number. This resulted in over two thousand information warnings of "Elements have duplicate 'Mark' values." As it was intended from the start of the design process, these information warnings were ignored (see Example D of Fig. 3).

Also in Project K, more effort was made to manage warnings management during the design process. Since this project was designed after the other two projects, experiences gathered from the previous projects benefited this project. This warning management effort reduced the number of annotation warnings, which are relatively easy to fix, and kept the share of the annotation warnings lower than the other two projects.

The same analysis was performed based on design phases, and Fig. 8 illustrates the shares of warning types in each phase. Geometry-duplication and information are consistently the two most frequent warning types, each accounting for around 30% of entire warnings in each design phase. Although the DD and CD phases indicate an almost identical pattern in terms of warning types, the SD phase shows a relatively larger share of geometry-duplication warnings than the other phases (10% more), but a smaller share of annotation warnings (15% less).

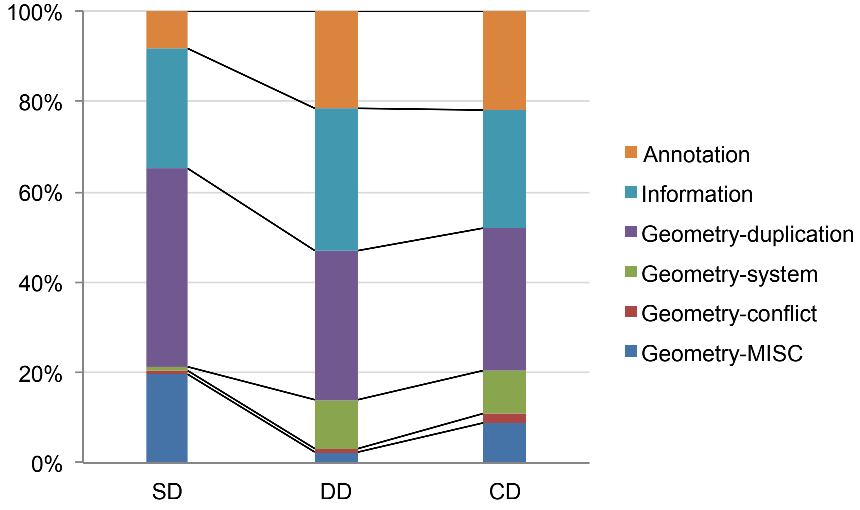


Fig. 8. Warning types by design phases

Again, the reason for the difference was investigated by interviewing designers. The investigation revealed that the nature of the SD phase again led to the identified unique pattern of warnings. As mentioned in the previous section, designers tend to carry multiple options in one model during SD for comparing the implications of overall design schematics. Resultantly, SD tends to have a higher share of geometry-duplication warnings than DD or CD. Such geometry-duplication warnings are simply ignored, because the purpose of SD is not to produce detailed design documents, but to develop overall design concepts that serve as a basis for the following phases. Furthermore, the kinds of drawings required for SD are significantly smaller than the other phases, and less annotation is needed for drawing production. As a result, models during SD have a lower share of annotation warnings than those of DD or CD.

8. TIME ESTIMATION FOR WARNING CORRECTIONS

Correcting thousands of warnings in the BIM models of a large project is necessary, but unfortunately time consuming. This section aims to help design companies efficiently manage their time by (1) differentiating priority levels of warnings, and then by (2) estimating time required to correct warnings.

As stated earlier, three priority levels (high, medium, and low) were employed to differentiate warnings by priority. Fig. 9 presents their shares of each priority in the three design phases. While the DD and CD phases indicated an almost identical pattern in terms of warning priority (5% for high, 65% for medium, and 30% for high), SD shows larger shares of high and low priority warnings and a smaller share of medium priority warnings.

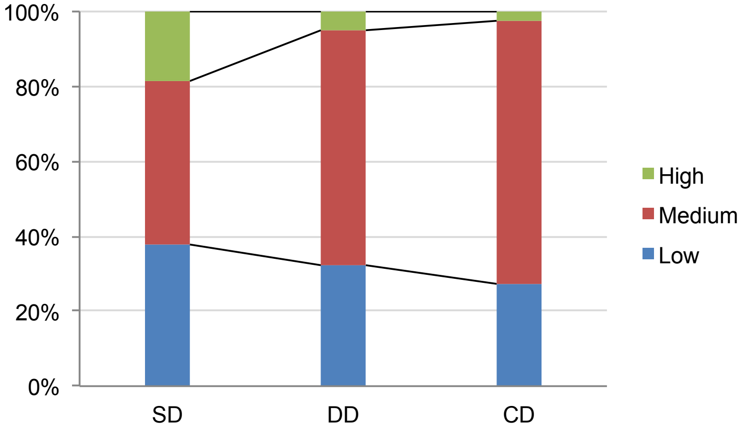


Fig. 9. Warning priorities by design phases

Based on the priority levels, time estimation was developed for warning corrections of each case project. The estimation started with a time study that was conducted by measuring the time taken to correct 10 warnings of each warning type. The study results showed that the average time of correcting annotation, information, and geometry warnings were 1, 0.5, and 5 minutes per warning, respectively. In addition, the follow-up interviews with the designers after the time study revealed (1) a number of warnings can be fixed simultaneously by taking just one action, especially for annotation and information warnings; and (2) a total time required for warning corrections can be reduced by working on the same type of warnings in succession. Learning curve theory based on Wright's Model [33, 34] is applied accordingly. Wright's Model states that the cumulative average time can be determined by Equation 1:

$$CAT_N = K(N^S) \qquad \text{Equation 1}$$

where CAT_N = cumulative average time per unit at the completion of N^{th} unit; K = time needed to complete the first unit; N = total number of units; and s = slope parameter = *log(L)/log(2)*, where *L* refers to a learning rate, i.e., the rate of improvement per doubled units. For example, *L* of 90% means that the time for completing the second unit is 90% of the time for the first unit. Thus, the total time required for warning corrections in each project can be estimated by using Equation 2:

$$Total\ Time = \sum_{i=1}^{n} K_i (N_i)^s N_i \quad \text{Equation 2}$$

where n = total number of warning messages in a project; K_i = time to correct the first warning of i^{th} warning message (1, 0.5, or 5 depending on the warning type); N_i = total number of warnings in i^{th} warning message.

We assume that designers would want to focus on correcting high and medium priority warnings while they may elect to ignore low priority warnings, which have little to no impact to the quality of models. As a result, Fig. 10 shows the estimation of total time required for correcting warnings of only medium and high priority in each project depending on assumed levels of learning rates. It shows that the total time exponentially decreases as the learning rate increases. For example, the total time required for correcting the entire warnings of Project K (a total of 5040 high and medium priority warnings) decreases from 8378 to 3589 minutes as the learning rate decreases from 100% (no learning effect) to 90%. This finding signifies the importance of assigning competent designers to the task of correcting warnings so that a steep learning curve is achieved during the otherwise time-consuming task.

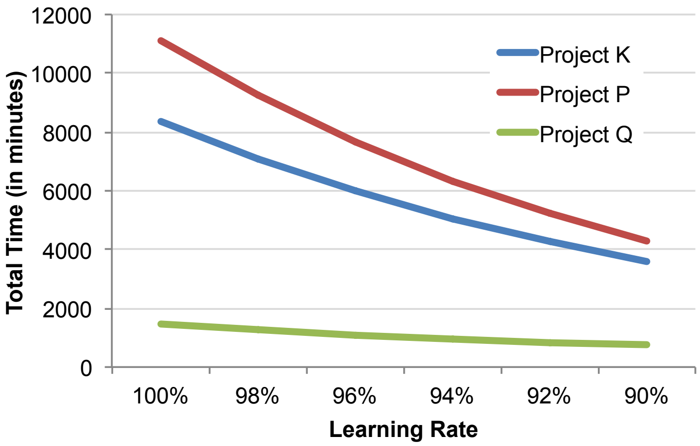


Fig. 10. Total time required for warning corrections based on learning rates

9. DISCUSSION

Detecting errors during design process had traditionally been a job of human beings through their cognitive processes [22, 23, 27]. However, BIM serves to automatically detect design errors, enhancing the human cognitive process in error detection. Thus, BIM can increase the efficiency of detecting design related errors and accordingly reduce design reworks [4]. It is achieved mainly by utilizing crash detection [2] and automatic warning messages, as presented in this study. Although designers must not solely rely on BIM for error detection, the designers that were interviewed during this study confirmed that they extensively take advantage of BIM warning messages on a daily basis as a way to detect and correct design-related errors. It is believed that BIM warnings can help to detect different types of design-related human errors (e.g., mistakes, slips, and omissions) by providing pre-defined warning messages issued for problems that are specific to model elements.

Another benefit offered by BIM warnings is that they provide a supplementary metric to the Level of Development (LOD) in measuring the completeness of BIM during design development. Measuring the development of BIM throughout design development is no easy feat as the design process is progressive and iterative by nature. In recent years, LOD has been suggested by a number of professional organizations (including the American Institute of Architects) as a method that "describes the level of completeness to which a Model element is developed" [35]. The five levels of LOD are LOD 100, 200, 300, 400, and 500, ranging from least to most descriptive. Each phase has model elements of varying LOD; for example, a model in the DD phase can have majority of elements at LOD 200, but also, some LOD 100 and LOD 300, and even LOD 400 [36]. Based on the findings of this study, it is expected that certain LODs can indicate unique patterns of BIM warnings. Therefore, if systematically incorporated, the inclusion of warning information (types, shares, and frequencies) can add more clarity to definitions of each LOD. For example, the descriptive warning patterns of LOD 100 can be compared to that of LOD 300, as performed in this study. Such a comparison is believed to contribute to the effectiveness of distinguishing different between LODs.

Lastly, the AEC industry still lacks formalized BIM practices. It is noticed that BIM practices that vary by companies and by projects would affect BIM warning management. Therefore, it is imperative to highlight the additional uniqueness of the three studied projects in terms of their BIM practices. Project P was commenced in 2005 as a BIM pilot project. At that time, BIM was just emerged and introduced in the industry. At the onset of this BIM pilot project, the design team immediately began to struggle with a number of trials and errors. This difficulty was attributed to the lack of information and understanding about BIM warnings and their impact on BIM performance. Further, BIM warning management was barely implemented around that time. Project Q was significantly smaller than the other two projects in terms of project size. Owing to the small project size along with its relatively lengthy design phase, a very selective small group of designers could be devoted to the BIM development. These three factors together substantially helped the designers to improve the efficiency of BIM modeling throughout the design phase. On the contrary, Project K was designed under a very aggressive project schedule. In response, a large cross-functional design team was formed to develop designs as quickly as possible. The team was suffered from the difficulty of BIM coordination among 20+ members, which was triggered mainly by the time pressure set forth by the owner. Educating novice team members about BIM tools and techniques created another challenge. It turned out that such a large number of users working concurrently on a single BIM model led to a large number of lags, crashes, and even losses of work over the course of the BIM development.

10. CONCLUSION AND FUTURE STUDY

Proper use of BIM warnings can not only minimize the occurrence of design-related errors, but also reduce time and cost that would be spent on design-related reworks. However, no identified study has investigated BIM warnings. To supplement lack of knowledge on this subject, the present study sought to investigate the types and frequency of BIM warnings by applying the Pareto analysis to data collected from case projects.

A total of 15,586 warnings were collected from three California healthcare projects of different sizes, types, and delivery methods. The warnings were then classified into six types: annotation, information, geometry-duplication, geometry-conflict, geometry-system, and geometry-MISC. Among the six types of warnings, geometry-duplication (34%), information

(29%), and annotation (20%) are the three dominant types of warnings that account for 83% of occurrences in total. The Pareto analysis confirmed the 15-80 rule, where 15% of the warning messages were responsible for nearly 80% of the warnings. Despite their differences in project characteristics, the rule was found to be valid regardless of project or design phase, except for the SD phase that displayed the 25-80 rule.

The study also showed that the SD phase indicates a different warning pattern from the other two phases by having a relatively large share of geometry-duplication warnings, but a small share of annotation warnings. The interviews with project designers revealed that the nature and purpose of the SD phase led to those unique patterns. During SD, designers carry multiple design options within one model for rapid comparison, which results in the increased share of geometry-duplication. Because the purpose of SD is not to produce detailed design and documents but to develop overall design concepts, such geometry-duplication warnings can be simply ignored. Also, models during SD simply do not have a significant amount of annotations, which results in a small share of annotation warnings.

As the last part of the analysis, the study presented ways to differentiate priority levels of warnings, and then to estimate time required for completing the task of correcting warnings. The time estimation was based on learning curve theory, demonstrating that the total time required for correcting warnings can be reduced significantly if a learning effect is expected from working on same warning types in succession. We expect that systematic time estimation for warning corrections based on priority levels should be part of efficient BIM warning management.

To our knowledge, this study delivers the first investigation of BIM warnings. The results presented in this paper drew on three projects designed by a single organization. Accordingly, we make no claims about the generalization of these results. However, we believe that the rigor of this study has provided insight and evidence regarding patterns and classifications of BIM warnings and the Pareto principle. The findings are expected to contribute to the design management and modeling practices of design teams involved in large, complex projects by proposing ways to signify the “vital few and trivial many.” Based on the findings of the study presented in this paper, three types of future studies are suggested: (1) warning data from more projects can be collected to further validate the identified Pareto principle and patterns of BIM warnings; (2) procedural protocols can be developed to manage BIM warnings based on their classifications; and (3) warning types of Revit can be compared to other BIM systems, such as ArchiCAD, MicroStation, Tekla, etc.

11. ACKNOWLEDGMENTS

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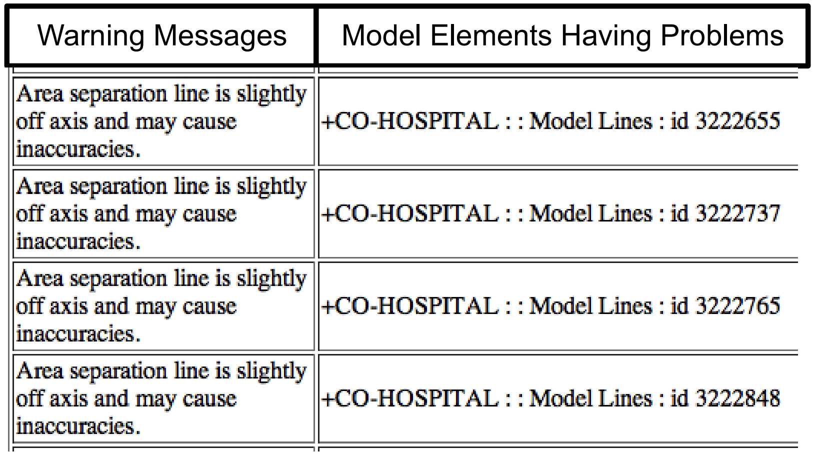


Warning Messages	Model Elements Having Problems
Area separation line is slightly off axis and may cause inaccuracies.	+CO-HOSPITAL : : Model Lines : id 3222655
Area separation line is slightly off axis and may cause inaccuracies.	+CO-HOSPITAL : : Model Lines : id 3222737
Area separation line is slightly off axis and may cause inaccuracies.	+CO-HOSPITAL : : Model Lines : id 3222765
Area separation line is slightly off axis and may cause inaccuracies.	+CO-HOSPITAL : : Model Lines : id 3222848

Fig. 1. BIM warning report showing warning messages and corresponding model elements (screenshot courtesy of CO Architects)

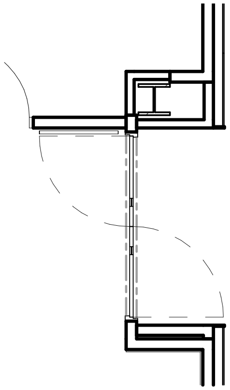
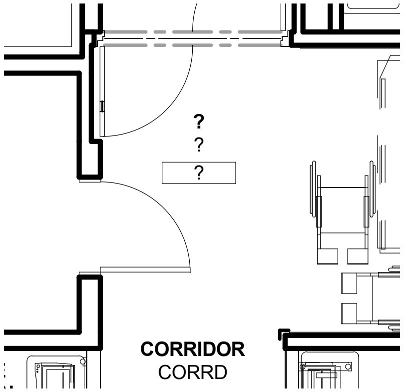
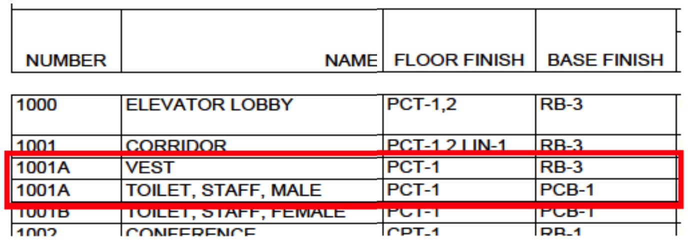
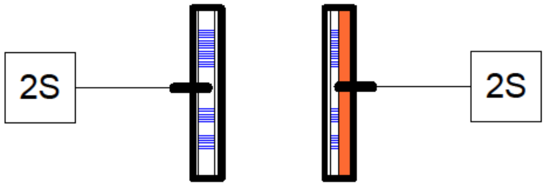
	Example A	Example B
Warning Messages	*An elevation symbol references views on more than one sheet. It will show a blank sheet reference. To show the correct references, use a separate elevation symbol for the views on each sheet.*	*Room Tag is outside of its Room. Enable Leader or move Room Tag within its Room.*
Priorities	High priority	Medium priority
Screenshots		
Descriptions	Two elevations were created from one elevation bubble that was placed on two different sheets. This resulted in a blank bubble where a sheet number is supposed to appear. This problem is not limited to one view but project wide, and can lead to confusion during construction.	The room tag is showing question marks because it was placed outside of its room boundary. If this happens within a working view, it is ignorable. If this happens within a contract drawing, it will cause confusion.

Fig. 2. Examples of annotation warnings (screenshots courtesy of CO Architects)

	Example C	Example D
Warning Messages	*Elements have duplicate 'Number' values.*	*Elements have duplicate 'Type Mark' values.*
Priorities	High Priority	Medium Priority
Screenshots		
Descriptions	Two rooms have an identical room number. Most room coordination is made possible by using room numbers. Thus, this can create issues during construction.	These two walls have the same structure but serve different purposes. In order to differentiate these two graphically, the design team decided to create two types of walls, but gave them an identical type mark.

NUMBER	NAME	FLOOR FINISH	BASE FINISH
1000	ELEVATOR LOBBY	PCT-1,2	RB-3
1001	CORRIDOR	PCT-1,2 LIN-1	RB-3
1001A	VEST	PCT-1	RB-3
1001A	TOILET, STAFF, MALE	PCT-1	PCB-1
1001B	TOILET, STAFF, FEMALE	PCT-1	PCB-1
1002	CONFERENCE	CPT-1	RB-1

Fig. 3. Examples of information warnings (screenshots courtesy of CO Architects)

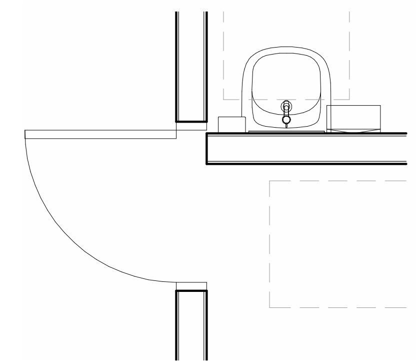
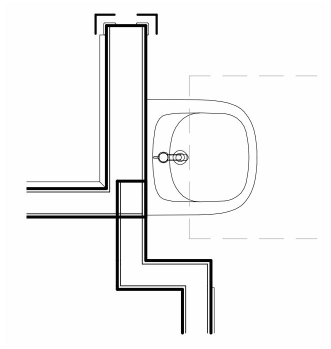
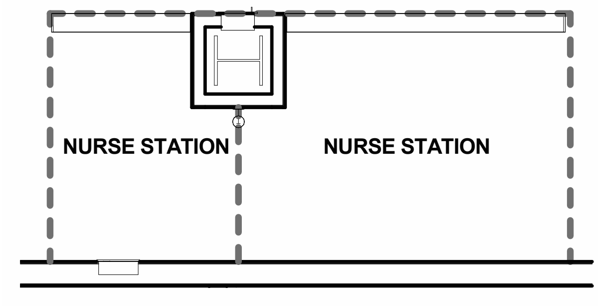
	Example E	Example F	Example G
Warning Messages	*Insert conflicts with joined wall.*	*Highlighted walls overlap. One of them may be ignored when Revit finds room boundaries. Use Cut Geometry to embed one wall within the other.*	*A wall and a room separation line overlap. One of them may be ignored when Revit finds room boundaries. Shorten or delete the room separation line to remove the overlap.*
Types	Geometry-conflict	Geometry-duplication	Geometry-duplication
Priorities	High priority	Medium priority	Low priority
Screenshots			
Descriptions	A wall joins at a door opening. This should not happen in construction, and has to be addressed immediately.	Two walls overlap. This is a common drafting mistake. Even though they do not directly affect construction, this mistake appears on the drawings, and needs to be fixed.	A room separation line (dashed line) overlaps with a wall. The design team intentionally ignored this warning because this affects neither the drawing nor the model.

Fig. 4. Examples of geometry warnings (screenshots courtesy of CO Architects)

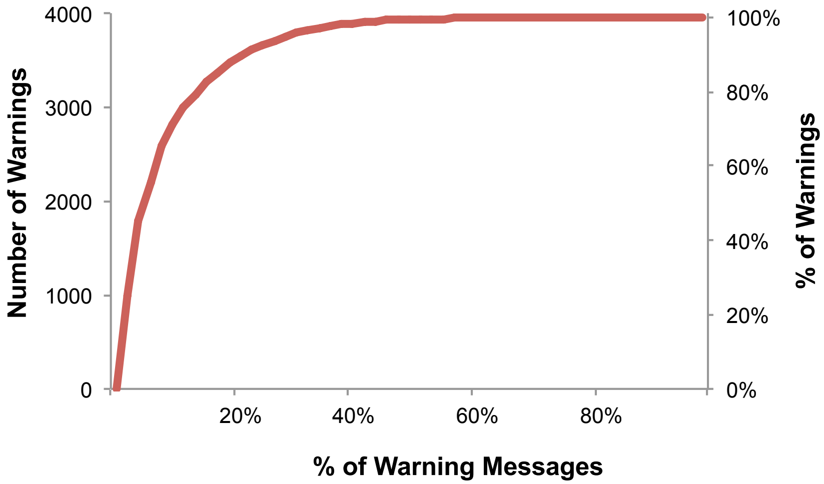


Fig. 5. Pareto diagram of warnings from three California healthcare projects

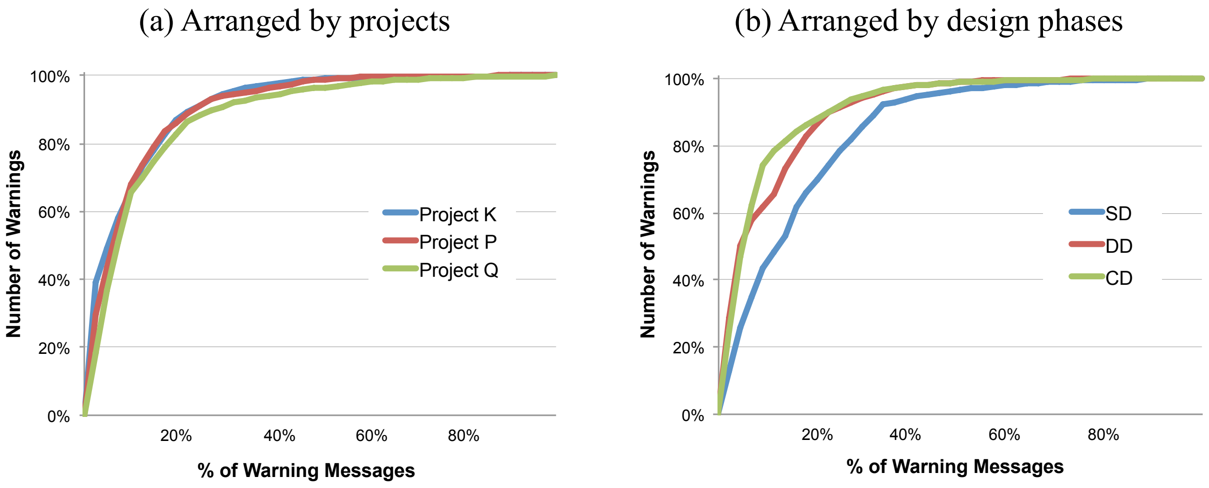


Fig. 6. Pareto diagram of warnings by projects (a) and by design phases (b)

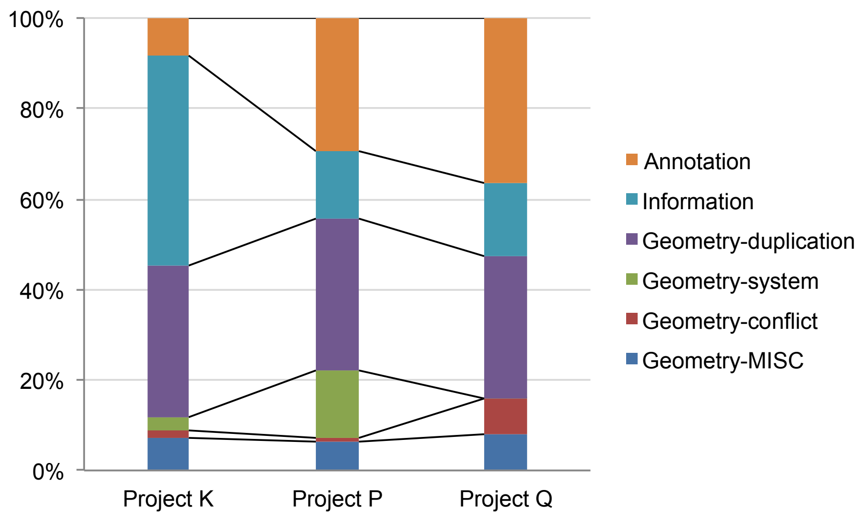


Fig. 7. Warning types by projects

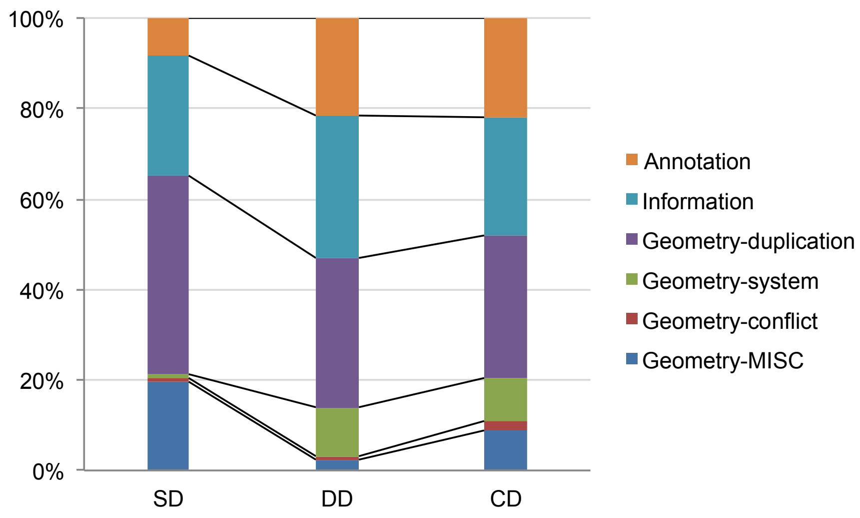


Fig. 8. Warning types by design phases

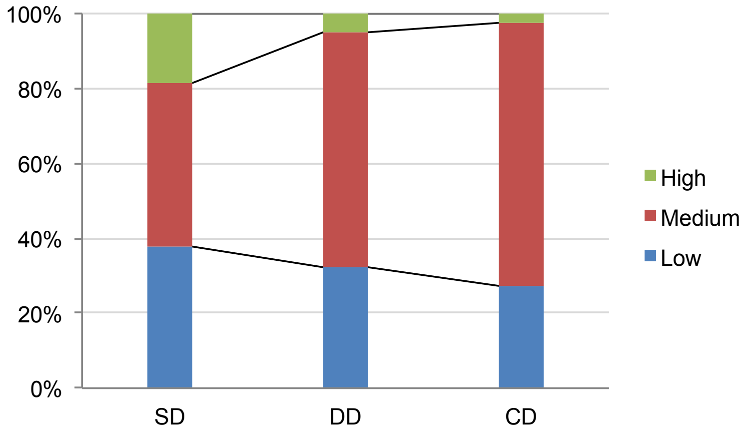


Fig. 9. Warning priorities by design phases

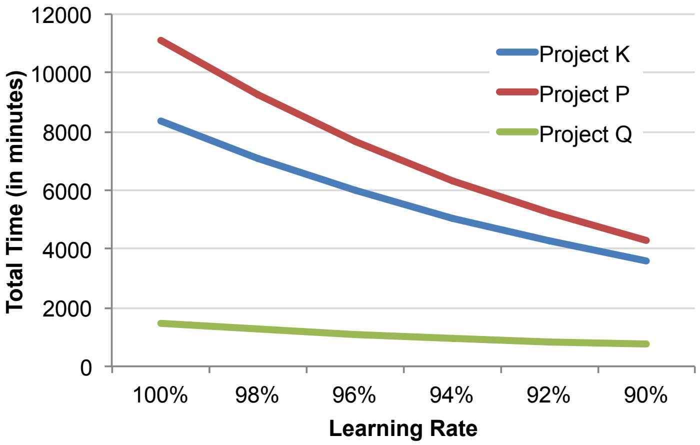


Fig. 10. Total time required for warning corrections based on learning rates

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Table 1. Warnings by types and projects

Warning Types		Warning Messages		Project K		Project P		Project Q		Total	
		Count	Share	Count	Share	Count	Share	Count	Share	Count	Share
Annotation		3	5.7%	573	3.7%	2390	15.3%	205	1.3%	3168	20.3%
Information		4	7.5%	3229	20.7%	1196	7.7%	89	0.6%	4514	29.0%
Geometry	Duplication	9	17.0%	2319	14.9%	2715	17.4%	176	1.1%	5210	33.4%
	System	13	24.5%	209	1.3%	1223	7.8%	1	0.0%	1433	9.2%
	Conflict	4	7.5%	112	0.7%	57	0.4%	45	0.3%	214	1.4%
	MISC	20	37.7%	494	3.2%	509	3.3%	44	0.3%	1047	6.7%
Total		53	100.0%	6936	44.5%	8090	51.9%	560	3.6%	15586	100.0%
Warnings per unit area of building (warnings/m^2)				0.14		0.12		0.08		0.13	