Information Visualization for Managing Large-Scale Engineering Projects

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***Abstract*—Building Information Modeling (BIM) employs 3D CAD models as a central knowledge base for large-scale facility design, construction, and operation. Its growing information complexity calls upon innovative techniques for effective visual analysis and exploration. An important question remains: how to best display relevant information for different use cases throughout a facility's life cycle? This PhD thesis seeks to bridge this gap through both theoretical and practical approaches. We first present a systematic literature review on the current state of information visualization (VIS) in BIM research. Building upon these findings, we describe the design and evaluation of a novel 4D system for virtual construction planning. Its unique visualizations make evident schedule uncertainties, workspace conflicts, and other constructability issues. The thesis contributes to BIM research with important visualization guidelines and also contributes to VIS research by raising awareness to interesting challenges in a increasingly relevant engineering domain.**[1]

I. Introduction

Building Information Modeling (BIM) is a set of methods and tools to improve management of large-scale construction projects [1]. BIM employs 3D CAD models as a central database for all physical, functional, and life-cycle information of a facility. This environment enables virtual analysis and simulations that improve quality of designs and work plans.

From its inception, BIM has been used for design checking and virtual construction planning [2]. Over time, it has evolved to other analysis, such as: work safety [3], asset management [4], and environmental sustainability [5]. For these reasons, governments around the world are encouraging the use of BIM in public enterprises [6]. Meanwhile, leading experts have developed guidelines and frameworks to accelerate its implementation [7]. Despite these efforts, BIM is yet to be widely adopted in the construction industry [8].

BIM systems face a major visualization challenge: how to best display relevant information for various analyses throughout a facility's life cycle? 3D CAD representations often struggle with perceptual issues of visual clutter and occlusion. BIM further enriches these designs with multidimensional metadata. The resulting complexity calls upon innovative techniques for effective visual analysis and exploration. However, this subject remains largely unexplored by both VIS and BIM research.

[1]PhD Thesis

This PhD thesis seeks to bridge this gap through both theoretical and practical approaches. First, Section II describes a systematic literature review on the state of information visualization in BIM. We consolidate our findings in a set of design guidelines for future research. Second, we build upon these recommendations to develop CasCADe: a novel 4D construction planning system (Section III). We describe how its analytical features improve previous work and make evident schedule uncertainties and conflicts. Finally, Section IV highlights future research directions enabled by our work.

II. Systematic Literature Review

Systematic literature reviews have been successfully employed in numerous areas of science [9]. They provide a means to present a fair evaluation of a research topic by using a trustworthy, rigorous, and auditable methodology. Following this scheme, we reviewed and categorized 140 research articles according to 4 taxonomies: Life Cycle Phases, Use Cases, Information and Data Types, and Visualizations. The study was designed to answer the following research questions:

1) What are the main use cases that employ visualization?
2) What are the project life-cycle phases of each use case?
3) What information are required by each use case?
4) What are the methods for visualizing this information?
5) What are the pros/cons of the current visualizations?
6) Which other visualizations could have been employed?

A. Application Areas of Visualization

Fig. 1 shows a heatmap and histograms with the statistical distribution of visualization applications from our review. Most research focus on construction planning and execution (70% of all articles). Other applications tend towards the design phase (21%), with an equal interest in *"Design Review"* and *"Sustainability Analysis"*. Only a few research focus on facility operations (9%), with main applications in *"Energy Analysis"*, *"Thermal Analysis"* and *"Maintenance Management"*.

A minority of works anticipated *"Facility Management"* analysis to earlier life cycle phases. There are also many use cases in *"Work Execution"* that remain yet unexplored by current visualizations. Moreover, future research could adapt

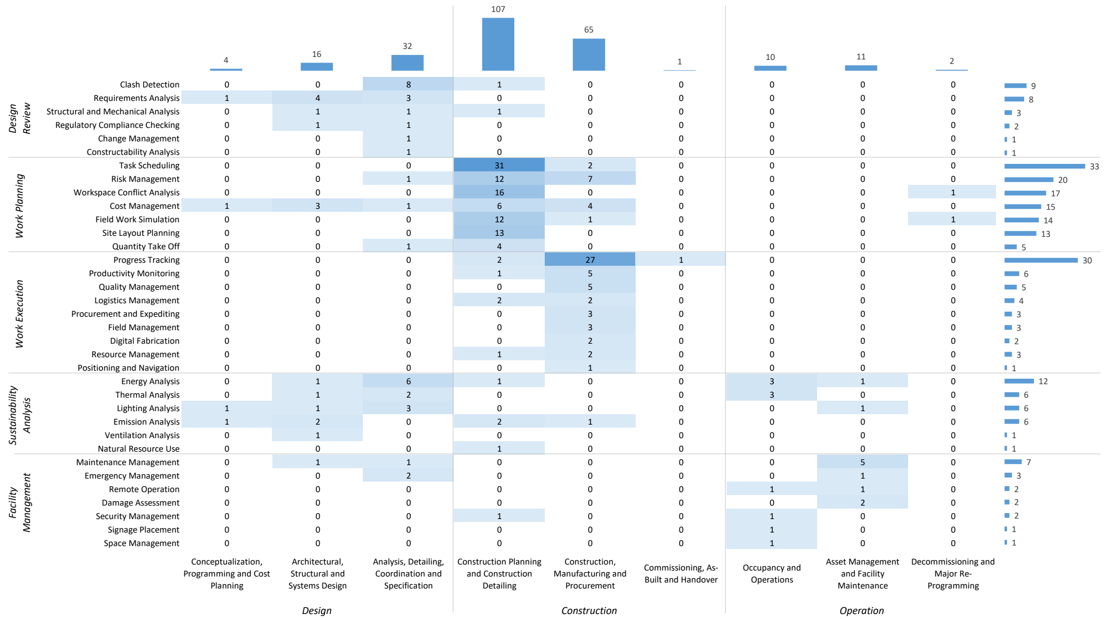


Fig. 1: Heat map and histograms showing the statistical distribution of visualization applications in BIM. Each cell contains its number of applications (darker cells show higher quantities). Horizontal axis: Life Cycle Phases. Vertical axis: Use Cases.

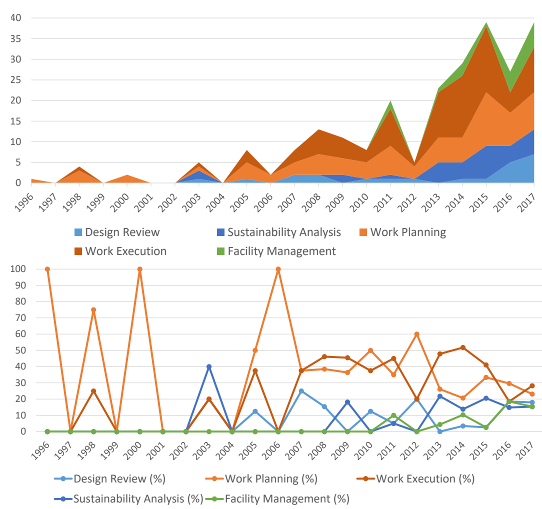


Fig. 2: Frequency of visualization applications in BIM. Top: accumulated. Bottom: percentages.

work planning and execution visualizations, traditionally used in construction, towards facility operations.

Until 2012, BIM was mainly used for construction planning (see Fig. 2). Only from 2007 onward that BIM saw major use in *"Work Execution"*. From 2012 to 2017, works in *"Sustainability Analysis"* and *"Facility Management"* have been steadily growing in number (from 4% to 33% of all works in each year). In the upcoming years, research interests should reach an equilibrium, with BIM applications spread equally across all use cases and all life cycle phases.

Within each use case, we can identify the following main application areas of visualization:

- *Design Review*: Clash Detection
- *Work Planning*: Task Scheduling
- *Work Execution*: Progress Tracking
- *Sustainability Analysis*: Energy Analysis
- *Facility Management*: Maintenance Management

B. Critical Analysis of Visualization Techniques

The thesis conducts a detailed analysis of the techniques employed in the aforementioned 5 main application areas. We have summarized 26 different visualizations, from Chart views (graphs and plots) to 2D/3D CAD views (annotations, highlights and animations). Each technique is studied according to the Views, Marks, Channels, and Information it employs [14].

In this article we include a brief analysis of techniques in *"Task Scheduling"*. Combining temporal with spatial information allows engineers to avoid many scheduling problems, such as inconsistent assembly ordering and workspace conflicts. Figure 3 indicates a large variety of visualization methods. Slightly more information is displayed in Chart views than 3D CAD views. Interestingly, the third column ranks visualizations from Chart and 3D CAD views in alternated fashion. Main techniques include: Gantt Chart, Visibility Animation, Table, Annotation, and Hierarchy.

Gantt Charts are the most popular visualizations to analyze temporal information (Fig. 4a). These diagrams plot time using the horizontal spatial dimension in an intuitive graph-like view. Tasks are represented by Line Marks with varying positions, lengths, and colors. Positions indicate start/finish dates while lengths show durations. Colors distinguish nominal/ordinal data: task types, criticality, and execution status.

Regarding the 3D CAD view, the most popular 4D visualization is the Visibility Animation (Fig. 4b). In this scheme,

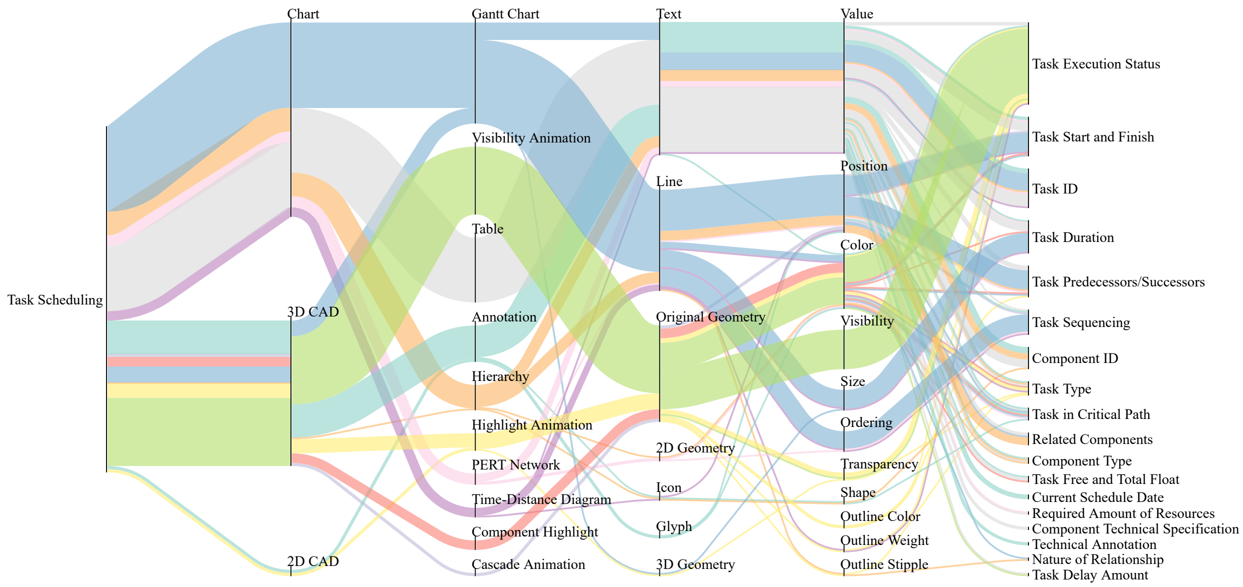
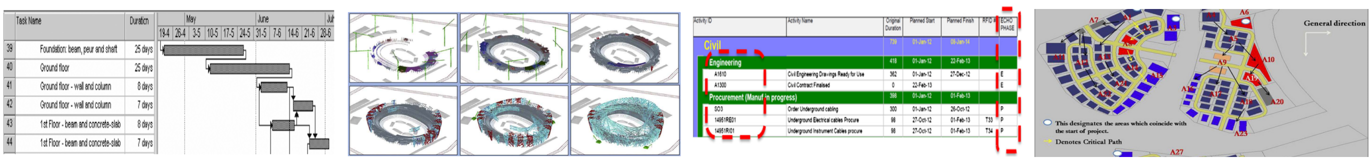


Fig. 3: Correlations among Views, Visualizations, Marks, Channels, and Information in *"Task Scheduling"*. Flow widths indicate frequency of use and colors distinguish visualization techniques.



(a) Gantt Chart [10]. (b) Visibility Animation [11]. (c) Table [12]. (d) Annotation [13].

Fig. 4: Examples of the top 4 visualizations in *"Task Scheduling"*.

facility components not yet built remain invisible and suddenly appear according to their construction sequence. This discrete animation makes it impossible to overview the entire schedule: geometries from future tasks remain hidden. Moreover, no Mark/Channel display task durations: they must be inferred from the length of time that objects are color-coded. Similarly, predecessors/successors must be deduced by the sequence of appearing geometries. For these reasons, previous research have long criticized this spatio-temporal visualization [15].

An alternative 4D visualization is the Highlight Animation. It changes several color-related Channels associated with original 3D geometries to display categorical information: task types, execution status, and predecessor/successor relationships. Quantitative data such as task durations are displayed in Tables or must be deduced from when the 3D geometries change in appearance. This results in many of the same limitations found in the aforementioned Visibility Animation.

Additional schedule information are displayed using Annotations, Tables or Hierarchies. Annotations are overlay 2D geometries and glyphs whose color and shape indicate task IDs, types, and sequencing (Fig. 4d). Tables are typically linked with the 3D CAD view to present context-sensitive metadata (Fig. 4c). Hierarchies indicate parent/child relationships using text, icon, and line Marks.

C. *Proposed Design Guidelines*

Table I summarizes our findings from the systematic literature review. From the issues observed in current BIM applications, we suggest overall design guidelines for future work. The thesis describes each topic in detail based on best practices of VIS research.

TABLE I: Visualization issues and proposed design guidelines based on the reviewed BIM applications.

Issue	**Guideline**	**VIS References**
Abundance of textual displays	Prefer graphical displays over text	[16], [17]
Lack of spatial context	Employ 2D/3D CAD views whenever possible	[18], [19]
Unrelated abstract and spatial views	Make better use of coordinated multiple views	[20], [21]
Laborious exploratory analysis	Call attention to features of interest	[22], [23]
Complex 3D CAD models	Reduce visual clutter and occlusion in 3D CAD views	[24], [25]
Animations as discrete snapshots	Use continuous animations to preserve context	[26], [27]
No spatial display of physical simulations	Take advantage of scientific visualization	[28], [29]
Inadequate color coding within 2D/3D views	Choose adequate color schemes depending on data types	[30], [31]

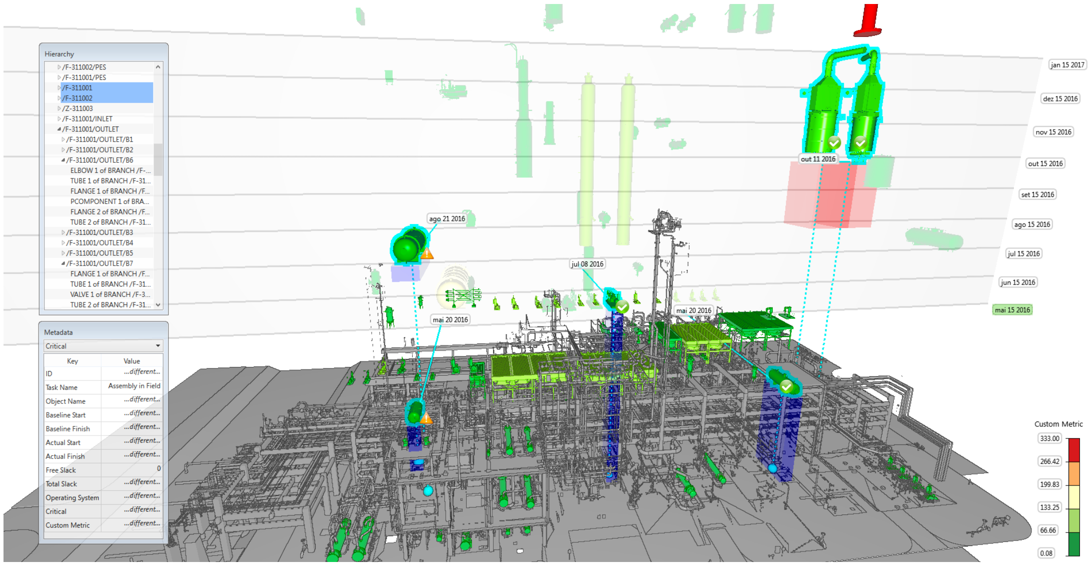


Fig. 5: CasCADe's unique 4D visualization combines the intuitive task sequencing from PERT/Gantt charts with the spatial awareness conveyed by 3D CAD models to bring forth problems and inconsistencies in engineering construction schedules.

III. CasCADe Visualization System

Motivated by the shortcomings identified by our literature review, we present our second contribution: the design of a novel 4D visualization system named CasCADe. Its core concept is to map time as a spatial dimension to create an effect of cascading equipment in a 3D exploded view (Fig.5).

A. Proposed Visualization Framework

CasCADe introduces a 4D visualization framework that uniquely combines the main features of 2D and 3D environments. Its main principle is to use one of the 3D CAD model's spatial coordinates to present time, similar to PERT/Gantt charts. Geometries are translated vertically along the *z-axis* according to the finish dates of corresponding schedule tasks. The remaining x and y coordinates preserve crucial information about each activity's location at the job site. A common frame of reference avoids any ambiguities: a horizontal plane that represents the "current date". The user can change the time scale and simulate the passage of time using a cascading animation. The final *z coordinate* of each object is computed using the following equations:

$$Z_{obj} = Z_{plane} + \frac{(FinishDate_{task} - CurrDate)}{(LastDate_{plot} - CurrDate)} * Size_{plot} \quad (1)$$

$$LastDate_{plot} = CurrDate + Count_{Interval} * Days_{Interval} \quad (2)$$

This unique environment brings many advantages over existing approaches. An overview of the entire construction plan is always available: at any moment, it is possible to glance upwards or downwards to identify future or past activities. Moreover, relative 3D positioning intuitively indicate tasks that occur simultaneously and physically near each other.

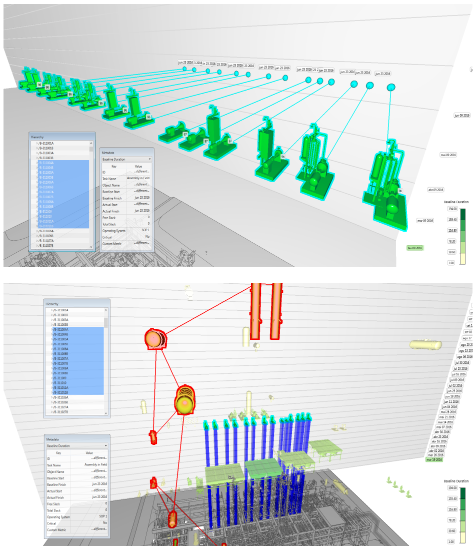
The choice of axis to plot time should reflect the main characteristics of the underlying 3D CAD model. For an Oil & Gas plant, the horizontal plane still preserve crucial positioning information to illustrate assembly locations. Depending on the type and physical layout of the facility, the visualization could use other axis combinations to plot time while preserving spatial locations. Similar to traditional exploded views, multiple cascading reference frames could be used simultaneously to illustrate assembly sequencing of complex parts.

B. Analytical Features of the CasCADe System

Table II enumerates the analytical functions implemented within CasCADe's visualization framework. The thesis describes in detail which problem-solving tasks are facilitated by these functionalities and compares them with related techniques from VIS literature.

TABLE II: Visual analysis functions in CasCADe.

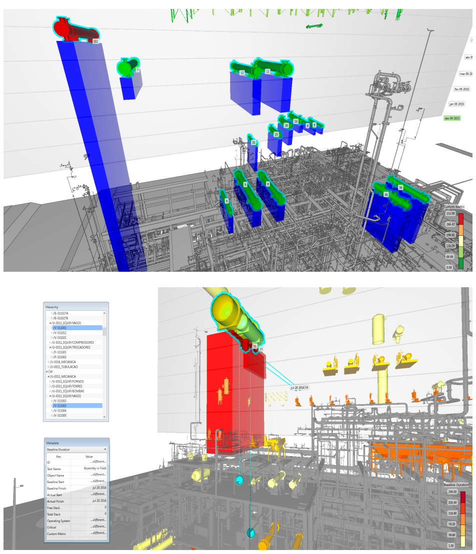
Use Case	*Analytical Features*	*Related Work*
1. Overview Schedule	Cascading view, projection aids, animation	Exploded views [32] Space-time cube [33] 3D interfaces [34] Animations [35]
2. Prioritize Tasks	Color coding, custom metric, focus+context shortcuts	Color perception [36] Color mapping [30] Focus+context [37]
3. Examine Metadata	Graphical overlays, linked views, *cascading view*, *projection aids*, *color coding*, *semi-transparent volumes*	Multiple views [21] GIS [38] Quantitative analysis [39]
4. Inspect Relationships	Highlights and links	Graphs [40]
5. Plan Site Layout	Semi-transparent volumes, *cascading view*, *projection aids*	Motion planning [41] Collision [42]



(a)

(b)

Fig. 6: Schedule uncertainties: (a) many parallel assemblies with long durations; (b) these tasks (blue bars) would compete for resources with the critical path (red lines).



(a)

(b)

Fig. 7: Constructability problems: (a) heat exchanger with unusually long duration (red); (b) work-space conflict of two overlapping geometries (red bars).

C. User Evaluation and Feedback

Engineering collaborators evaluated CasCADe using the construction plans of an Oil & Gas process plant. Our unique 4D visualization made apparent several uncertainties in the schedule (Fig. 6a). The system also exposed resource conflicts with the project's critical path (Fig. 6b).

The collaborators used CasCADe's custom color metric to determine which assemblies had the higher probability *vs* impact of compromising the schedule. One heat exchanger stood out with an excessively long assembly duration (Fig. 7a). CasCADe also made evident several work-space conflicts in the construction plan (Fig. 7b) If this work-space conflict was not observed prior to task execution, it could lead to high-risks for construction workers on the floor below.

Overall, the experts demonstrated a high degree of satisfaction with CasCADe, often highlighting the intuitive perception of task sequencing and their locations on the job site. They also praised the ease to analyze diverse time information in the same view using different user-customizable effects.

IV. Future Research Directions

Throughout this thesis, we have identified many opportunities for future work:

Evolving CasCADe's visualization framework: Order-independent transparency [43] and analytical features for schedule comparison [44].

Improving visualization in BIM: Follow the design guidelines from Table I and validate with case studies [45], [46].

Exploring synergies among use cases: Visualizations could make evident the effects of inter-dependent datasets (e.g. resources *vs* durations *vs* costs).

Extending use cases to other life cycle phases: Work planning/execution could be applied to later operation phases and sustainability analysis to all life cycle phases.

Future reviews based on our contributions. Graphs and statistics could find correlations in our dataset, future reviews could replicate our method, and the proposed classification framework could aid both BIM and VIS research.

V. Conclusions

This PhD thesis has aimed to improve the effectiveness of information visualization in Building Information Modeling (BIM). Due to space constraints, this article only presents a brief summary of many detailed analysis from our research. We first described the findings of a systematic literature review on the current state of visualization in BIM. Motivated by this analysis, we presented the design of an innovative 4D visualization system named CasCADe. These theoretical and practical contributions open the door to interesting new challenges for visualization in BIM.

Publications

The research in this thesis has been published in one journal article [47] and one conference paper [48]. We are awaiting review results of a third article submitted to *IEEE TVCG*.

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