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Grand Challenges in Data and Information Visualization for the Architecture, Engineering, Construction and Facility Management Industry

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ABSTRACT

This study aims to identify challenges in the AEC/FM industry that can potentially be addressed using research in data and information visualization. These challenges were recognized by reviewing visualization techniques for addressing current challenges associated with decision-making tasks; studying the fit between visualization techniques and the decision-making tasks; identifying the gaps in knowledge of visualization techniques; and finally establishing a framework for measuring the domain requirements and the technology capabilities as a road map for domain-needs-driven development in the area of data and information visualization. The challenges associated with the current practice of project delivery and the limitations of the state-of-the-art visualization techniques in addressing these challenges are discussed. This paper presents where and how intuitive and effective visualization can address these challenges. It also suggests areas where researchers can apply visualization research to further improve existing processes.

INTRODUCTION

In today's AEC/FM industry, project teams must collect and deal with a large variety of project data and information to support high-quality and timely decisions. Nonetheless, current representations do not effectively communicate project data and information, and have difficulties in highlighting their relationships. Consequently, project teams spend significant time mentally relating project data and information and manually performing decision analysis. The empirical observations on project teams using visualization techniques have anecdotally shown that the effective communication of project information and their relationship can significantly improve the decision-making process. There is a need to identify what kinds of visualization techniques are best suited for supporting various decision-making tasks in the delivery of AEC/FM projects. This study aims at identifying those project delivery challenges that can possibly be solved using data and information visualization tools.

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RESEARCH METHODOLOGY

An extensive literature review was conducted to find those challenges faced by the practitioners within a typical project delivery lifecycle that can potentially be addressed through research in data / information visualization. These challenges and the limitations of the current visualization methods are presented in the following:

AEC/FM CHALLENGES FOR DATA/INFORMATION VISUALIZATION

During various stages of a project, practitioners are faced with the need to easily and quickly make decisions. These decisions are primarily based on the data and information that can be derived from the very large datasets required to represent the various facets of a project. How best data/information can be presented from these large datasets is a fundamental research question. This question is particularly important in the AEC/FM community, because data and information visualization tools are directly usable by practitioners for improving decision-making (Korde et al. 2005; Golparvar Fard et al. 2006; Chiu and Russell 2011). In the following, practical problems and the needs within each stage of a project are discussed:

1. Design Development, Design Coordination, and Value Engineering: The needs for visualization tools during programming, and schematic/detailed design phases can be divided into: 1) tools that facilitate collaboration in interactive workspaces wherein experts are working together in a physical space; and 2) virtual workspaces wherein experts are working remotely and functionalities can be synchronous/ asynchronous.

a. Physical Workspaces: Current challenges in physical workspaces include no direct cost feedback on design decisions, lack of coordination of trades, and inability for reusing design data for shop drawings because architects and structural engineers - due to different regulations - model buildings in different ways. There have been advances in detection tools that can find collisions between structural elements and MEP systems. However, without an as-built model of a physical space, it is still very challenging to apply these model checking tools to existing structures for remodeling or retrofit design purposes. Although laser scanning and photogrammetry have been used to create as-built models of existing facilities (e.g., Tang et al. 2012, GolparvarFard et al. 2011), their application is still labor intensive and the computational burden for processing data is still pretty high.

b. Synchronous/Asynchronous Virtual Workspaces: Virtual workspaces are cloud locations where data/information is shared through electronic means. Research has shown that these workspaces improve the utility of project information and the quality of the decision-making (e.g., Liston et al. 2001, Golparvar-Fard et al. 2006). Others have shown adoption of virtual tools such as Second Life can further enhance global virtual collaborations (Iorio et al. 2010). Current challenges include managing 3D BIM on interoperable protocols to support queries in multiple/ individual models; visualizing semantic models using web-based interfaces accessible in smart devices; enabling multiple-use real-time environments wherein users can combine partial BIMs, linking BIM data to GIS programs, and the ability to share with cloud-based structural analysis tools. Also there is no measurable account of usage patterns with qualitative measures of how visualization tools are used in productive ways (Iorio et al. 2010). The mismatch between the value of desktop sharing for design coordination in virtual spaces and the lack of use by design project networks are other challenges. Addressing these enables better understanding on how underlying functionalities built into virtual environments can be beneficial to virtual workspaces.

2. Model-based Cost Estimation: Visualizing buildings in 3D removes a good deal of uncertainty for cost estimation. It no longer takes an estimator with the knack of creating 3D buildings in his head based on 2D drawings to fully appreciate what s/he sees (Words & Images 2009). 3D Model-based cost estimation is proven to be a leaner approach integrating BIM object attributes with cost databases (Tiwari et al. 2009). BIM ensures a unique source for cost estimating for the entire lifecycle (Azhar 2011). Compared with traditional approach, model-based cost estimation enables adjustment of the budget from one design scheme to another, estimates cost differences, and provides rapid feedbacks. Tiwari et al. (2009) points out that modelbased estimating process will eventually be faster than traditional methods. The challenges of visualized cost estimating go beyond finding the right combination of software applications. Various types of cost databases are currently being used by the industry. Standards for the level of detail are not yet defined for many applications (Hartmann et al. 2008). Nowadays it is practically difficult to use same visual tools to estimate project cost for collaborative companies. Another challenge is the integration of workflows between 3D/4D and 5D applications (Forgues et al. 2012). The process of tallying 3D elements from spreadsheets and establishing relationships between quantity take-off items and recipes is time consuming and is prone to human error. Software interoperability might lead to such errors as well. How to use model-based cost estimation to generate visualizations for decision making processes is yet another challenge. Moreover most cost estimating tools do not support dynamic processes in early design phase where many changes are still possible (Tulke et al. 2008).

3. Scheduling and Constructability Reasoning: Despite the benefits of clash detection with 3D model and the detection of space-time conflicts using 4D models current clash prevention tools cannot easily visualize non-physical type of interferences (i.e., soft conflicts) concerning issues like clearances (e.g., cable tray requiring clearance on the top for access), or functionality (e.g., conduits blocking the air flow) which are critical in developing coordinated models. Current tools can identify conflicts that occur in clearance spaces around building elements (e.g., clearance spaces for access); however, to identify majority of the soft conflicts, more research needs to be done to explicitly consider the functionality, performance, tolerance, safety, and installation requirements (Golparvar-Fard et al. 2006). Recent studies by ENR (2012) shows the majority of the benefits observed from applications of BIM are still being reported in clash prevention. While 4D models can provide compelling visualizations for schedule quality control and contractor coordination, yet their applications are still limited. The main challenges are the lack of tools that can easily visualize the site layout beyond the actual construction related elements; the challenges associated with visualizing dynamic operations (e.g. equipment) or temporary objects (e.g. scaffoldings); and finally difficulties in quickly visualizing 4D models with the as-built information for facilitating contractor coordination processes.

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4. Construction Performance Monitoring: a. ***Progress/Quality Monitoring*** require visualization of appearance-based and physical deviations between as-planned and asbuilt models. Research studies (e.g., Golparvar-Fard et al. 2011, Bosché 2010) have shown these models can be jointed visualized facilitating identification of deviations. Golparvar-Fard et al. (2009b and 2007) proposed application of metaphors based on traffic-light color to jointly visualize physical deviations and Earned Value Analysis metrics. In some cases, analyzing individual deviations and the correlations among them are important to to understand how progress/ quality issues are caused by shared reasons and how they influence one other. The challenges related to visualizing geometric differences lie in the computational complexity of detailed deviation analysis. Recently developed spatial data structure and change analysis algorithms can efficiently handle detailed geometries captured in dense and large 3D data sets (e.g., point clouds generated by photogrammetric or laser scanning systems).
Examples of such developments include Octree based change detection (GirardeauMontaut et al. 2005; Zeibak and Filin 2007), feature-based spatial change analysis (Choi et al. 2009), and multi-resolution voxel for efficient neighborhood searching and comparison (Olsen et al. 2009; Truong-Hong et al. 2011; Golparvar-Fard et al. 2013). These efforts reduce the computational complexity of comparing spatial data sets capturing cm-level details, while some challenges of extra-large spatial data (e.g., Terabytes of 3D data sets collected by 3D mobile mapping systems) remain, including effective data decomposition, data interoperability, and large number of parameters that need to be configured by engineers (e.g., color map, neighborhood size) (Anil et al. 2012). Visualization technologies generate spatial distributions of deviations, but it is time-consuming and error-prone to have engineers manually configure geometric comparison algorithms and inspect deviations. Comparing nongraphic attributes between the as-planned/as-built objects requires reliable data-object association, nongraphic feature recognition (e.g. material) and semantic visualization. These challenges still involve some open questions. For congested sites with large number of elements, associating the as-built data points with the closest as-planned objects may be misleading (Bosché 2010; Tang and Akinci 2012a). Without reliable correspondences between data and model, the relevant nongraphic attributes of objects are not comparable. Research studies are addressing reliable classification of materials based on imagery data (Golparvar-Fard et al. 2012; Zhu and Brilakis 2010), while lighting conditions, material properties, and uncertain environmental conditions can still cause less reliable recognitions. Finally, visualizing differences may involve categorical attributes such as materials or strength levels which are not numerical and ordinal. Visualizing such differences is still difficult as methods for detecting scale and semantic issues of categorical differences are under development.

5. ***Productivity and Operational Efficiency:*** Construction operations can be dynamically visualized by linking Discrete-Event Simulation and CAD models of the infrastructure, equipment, temporary structures, and other resources (Kamat et al. 2011). These models can serve as great communication tools for coordination, and validating the underlying logic of operational plans for maximizing productivity and operational efficiencies. Nonetheless, visualization of dynamic operations at a meaning-full level requires significant amount of operational details. Despite significant research in

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automated activity analysis over the past few years, more research needs to be done to enable the benefits of these visualizations.

6. ***Environmental Impacts:*** Several new carbon footprint monitoring tools are recently developed (e.g., Shiftehfar et al. 2010; Memarzadeh et al. 2012) that enable practitioners to effectively benchmark, monitor, and visualize expected and released embodied/actual carbon footprint of a project. These visualizations provide practitioners with an opportunity during coordination, submittal, and onsite construction processes to not only insure timely delivery of materials, but also minimize the cradle-to-site and onsite carbon footprint of their projects. The main challenge associated with visualization for embodied carbon footprint lies in the need for access to detailed datasets, and for actual carbon footprint lies in methods that can continuously track and localize equipment and their activities within 4D BIM.

7. ***Construction Safety:*** The challenges with visualization of construction safety in the design phase are related to challenges of modeling operational details and temporary structures such as scaffoldings and railings. During the construction phase, the challenges are rapid as-built modeling and integration with expected site models.

4. Building and Infrastructure Performance Metrics

a. Energy Performance Monitoring: Sustainable buildings have been a popular subject of study in the AEC/FM industry. The LEED rating requires energy modeling to assess the energy use of a building and to quantify the savings attributable to the proposed design. Currently an energy model can be directly created by importing BIM into a graphic energy modeling tool. For new buildings, BIM typically generated in the design phase can be directly used to conduct the energy performance analysis. Nonetheless, extensive manual modeling needs to be done in the design phase to import these models into the energy simulation tools. For accurate assessments, both geometry of the model and the semantics related to the thermal envelope (e.g., dimension and location of doors and windows, thermal zones, material types) have to be precise. For existing buildings, BIM is not always available. Even though BIM may exist, though these models might not be up-to-date. The preparation for new model is usually time-consuming, labor-intensive, and costly. Thermal zones and thermal information of the envelope also need to be manually obtained and assigned to the model for energy performance analysis purposes.

b. Health Monitoring: The challenges are mainly from the fact that large data sets are needed for capturing histories of monitored facilities, visualization of relative measurements, reliable health index generation and time series visualizations. Previous studies show the technical feasibilities of visualizing deformation histories of highway structures (Jaselskis et al. 2005), while pointing out the challenges of handling large data sets that are collected in multiple data collection sessions for capturing the life-cycle changes of such structures. For reducing the computational needs for visualizing deformation histories from large number of data sets, several studies use feature based approaches for monitoring purposes (Choi et al. 2009; Lim and Suter 2009; Teizer et al. 2005). These studies focus on visualizing geometric differences, while in many cases health monitoring agencies require tracking the changes of relative measurements (distance between certain features, alignments) (Tang and Akinci 2012b). Visualization of relative measurements still requires further explorations. Health monitoring requires visualizing the time series of health indexes of structures. Deriving structural index values from data is still an active research area (Olsen et al. 2009; Park et al. 2007). Furthermore, visualizing deterioration histories of structures require further explorations as to how to represent as-is histories together with the as-designed reference model. More research is needed to figure out how visualization of different parts of a structure with different health conditions and deterioration patterns can be handled.

5. Education in AEC/FM: The need for collaboration in the AEC/FM industry is growing to meet the needs of rapidly delivering high quality projects with lower budgets (Salazar et al. 2006). The industry is currently facing training crisis with aging workforce and little effort to utilize visualization techniques (Goedert et al. 2011). Gier (2007) believes that visualization tools within Construction Engineering and Management curriculum improve students’ abilities on process. Salazar et al. (2006) state that the major benefits for students learning visualization tools include: 1) developing a better understanding of buildings and their components; 2) achieving advanced skill for industry career or research purpose. However, the primary challenge is that education has to face constant update to accommodate the emerging technologies, which could be heavy burdens to instructors. The selection of the software to be used for class should evolve appropriately with up-to-date standards (Sah and Cory 2009). Without prior experience with visualization tools, students might have low performance on those projects that benefit from visualization. Many researchers have pointed out that virtual learning environment through Internet are extended beyond physical reach of classrooms, and can complement traditional CEM education (Koskela et al. 2005; Sawhney and Mund 1998). Second Life platform and role-playing scenarios have been explored as means of communication tools to satisfy the interactive learning in classrooms. Goedert et al. (2011) developed a systematic, game-based framework for combining construction simulation scenarios and learning, but expanding the base and breadth of modulus for learning is pending to be addressed. While Second Life provides a communicating interface, it lacks functions for reviewing multiple designs from 3D models (Ku & Mahabaleshwarkar 2011).

6. Frameworks for Assessment of Decision-Making Processes: Although most information is generated electronically for coordination meetings, teams still primarily communicate and share information using paper-based representations. Emerging technologies such as touch-sensitive large-screen displays, table-top displays, and tablet PCs offer great promise in enriching today’s paper-based workspaces to create what are known as interactive workspaces (Golparvar-Fard et al. 2006). 3D BIM tools are also gaining acceptance and provide benefits to the coordination process. It remains unclear as to how such tools can be incorporated in workspaces to support coordination. There is still a need for frameworks that can assess the impact of visualization on decision-making and coordination meetings.

CHALLENGES IN VISUALIZATION TECHNIQUES

1. Data and Information Granularity/Quality: It is essential to define the correct level of detail by data range (e.g., entire vs. a subset) or granularity (e.g. all vs. spread footings). Not only range and granularity of data is important for effective visualization, but it is also a source of reference for resolving potential conflicts. Despite advancements in visualization, it is still challenging to efficiently process large amount of data and visualize the only required subsets.

2. **Computation:** The rapid improvements in computer software/hardware have provided engineers with powerful methods of storing, processing, sharing, retrieving and visualizing data (Abudayyeh et al. 2004). These improvements have made visualization as a growing and essential part in many areas, such as monitoring for safety, progress, productivity, and virtual walk through. Visualization technologies in areas such as point cloud/image/video processing, and augmented reality have also become prominent. In spite of the feasibility of visualization techniques, it is still challenging to efficiently process the massive data collected from the construction sites, which could include 3D point cloud, 2D images, video frames, and other sensor data (Cho et al. 2012; Ham and Golparvar-Fard 2012; Gong et al. 2011). Point cloud data can easily reach hundreds of megabytes depending on the size of a construction site. The computation time exponentially increases when iterative algorithms are used to process the data. Another challenge is how to update visualization in real-time to assure the data authenticity for dynamic construction environments (Gai et al. 2012).

3. **Interaction:** It is essential to apply data fusion and conversion to satisfy user’s needs. Wang et al. (2013) introduced a color coding method for fusing temperature data with point clouds. Golparvar-Fard et al. (2007) suggested overlaying as-planned models on photographs and formed a method for visualization of construction progress where deviations were represented in Augmented Reality environment such as ones developed by Behzadan et al. (2007 - 2009). Using metaphor of traffic light colors, progress deviations were visualized in comprehensive single imagery. The findings from these studies on as-built data collection, as-planned modeling and visualization of progress form a stepping stone upon which the proposed framework for interactive visualization of construction progress with the D4AR – 4D Augmented Reality- modeling method is developed. Such semantically-rich project models can support various project management and facility management functions. Integrating as-built and as-planned models also provides an opportunity to assess deviations between as-design and as-built conditions (Akinci et al. 2006).

CONCLUSION

This paper aimed at identifying those challenges across typical steps of a project delivery that can possibly be solved using data and information visualization tools. These challenges were discussed at individual stages within a project delivery and the gaps in knowledge from the perspective of data and information visualization tools were discussed. Due to page limit, complete evidence regarding the severity of the challenges is not presented. The different visualization methods discussed in this paper can be employed to make better decisions or to help solve current AEC/FM communication problems. The visualization challenges can also possibly help researchers define their research directions.

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