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Analysis of empirical data on the effects of the format of engineering deliverables on craft performance

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ABSTRACT

A key component to craft success is the quality and fluency of the information at hand. Developments in three-dimensional (3D) computer aided design (CAD), mobile computing and 3D printing provide opportunities for engineering deliverables in new mediums at the face of the work. However, they are not being utilized to their full potential. This research examines the influence that the format of engineering deliverables in the form of two-dimensional (2D) plan sets, 3D CAD via mobile computing, and 3D printed models have on craft performance in completing tasks within a controlled setting. This research discovered that the format of engineering deliverables do influence craft performance while controlling for spatial cognition.

1. Introduction

The authors examine how the format of engineering deliverables influence craft performance in completing a "mock" task within an experimental setting. In these experiments, craft performance was measured based on the time to complete the task, direct work, indirect work, rework, and installation errors. In many ways, the experiments described herein are an extension of Dadi et al. [5–7], which found significant relations between individual cognitive demand and engineering deliverable formats, but were not able to fully identify a relationship between the format of engineering deliverables and craft performance [6]. Using a different experimental design, the authors discover that the format of engineering deliverables do influence craft performance controlling for individual spatial cognition.

2. Background

Engineering deliverables are a primary outcome of the design process and used by craft to build a project. In this context, engineering deliverables are the plans and specifications required by craft to execute the tasks and processes at the construction workface. Despite dramatic improvements in the interface design of engineering systems as represented by realistic visualizations and advancements in building information modeling (BIM), the format of engineering deliverables at the workface has broadly remained unchanged [16]. Even today, the primary format of engineering deliverables at the construction workface is two-dimensional plan sets of drawings or work packages. The authors explore the effects on craft performance when engineering deliverables of different formats are provided to the research's participants in completing a "mock" construction task.

Despite being used for thousands of years, engineering deliverables in the form of two-dimensional drawings are still problematic on construction sites. Liberda et al. [21] asked industry professionals to rank 51 factors effecting construction productivity under the categories of human manpower, management, and the external environment. Lack of information necessary to perform construction ranked 8th out of 51 overall factors as being a significant barrier to craft productivity [21]. Informational issues are even more drastic in the opinion of craft workers. The Construction Industry Institute (CII) interviewed close to 2000 construction workers to discover issues that hindered construction craft productivity. Three of the top ten issues were related to both the availability and accuracy of engineering drawings [8]. These findings suggest that changes in the practices of providing craft of the engineering deliverables necessary for construction are warranted in improving their performance.

2.1. Formats of engineering deliverables

While the traditional format of engineering deliverables is two-dimensional drawings, technical advances obviously now provide the delivery of engineering information in alternative formats.

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2.2. Two-dimensional drawings

The main format of an engineering deliverable used for most construction craft, two-dimensional (2D) drawings, has remained relatively unchanged for years. The last significant change in 2D drawings occurred in 1795 when French mathematician Gaspard Monge published *Geometrie Descriptive* proving that all spatial problems can be solved graphically using two or more projection planes [2]. Descriptive geometry is still the basis for displaying the same 3D object in multiple 2D views used by modern information systems.

2.3. 3D computer aided design (3D CAD)/(BIM)

3D computer aided design (3D CAD) in the architectural, engineering, and construction industries has evolved into integrated BIM, which is defined as models that contain graphical, data, and behavioral attributes, consistent and non-redundant, and coordinated data between platforms and trades [11]. Commercial developments in 3D CAD/BIM systems offer promise of pushing engineering deliverable information to the construction workface through the use of mobile computing devices. Previous research identified the overall framework of utilizing mobile computing devices [33], but recent research has focused on specific application of mobile computer applications in construction related to the integration of mobile devices and sensor agents [9,10,20,25,27,31] and the utilization of wearable computing devices [14,26]. While the use of 3D CAD/BIM models has become prevalent in design and planning, their direct access and use at the construction workface for the purpose of providing engineering deliverables remain relatively rare (Goodrum and Miller 2015), and prior research confirms that the main format of engineering deliverables continue to be paper-based plans and files [3].

2.4. Physical scaled 3D models

Physical scaled models were traditionally used in the construction industry as planning and communication tools. Models consisted of the entire project or individual elements built to scale and were traditionally used as checks on design and for planning construction sequences [29]. Traditional scaled 3D models were made by hand and expensive to build and maintain (Goodrum and Miller 2015), however modern 3D printers offer the potential of developing scaled 3D models much more efficiently. While scaled 3D models are rarely used on jobsites today, it should be noted that full scale models, commonly in the form of "mock walls", are still used, especially in the commercial building sector, as a method of illustrating final design details to owners and construction specialties. While there is potential use for 3D printed scaled physical models in construction field use, the conversion of a 3D CAD/BIM model to a format suitable for 3D printing technology requires extensive remodeling to satisfy current 3D printing file format requirements (Goodrum and Miller 2015), so their current use among construction crews remains rare.

2.5. Engineering deliverables and cognitive demands

This line of research addresses two dimensions of cognitive demand: spatial cognition and mental workload demand. While these are intertwined, previous research has examined them separately.

2.6. Spatial cognition

Regardless of the information medium of an engineering deliverable given to workers, craft must comprehend it to successfully complete their tasks. Like all individuals, craft have a finite spatial cognition with which to process the information. When interpreting engineering information, workers use their spatial cognition, specifically spatial orientation, which is the ability to, "perceive spatial patterns or to maintain orientation with respect to objects in space" [12]. When interpreting spatial information, an individual's spatial cognition ability allows them to create and manipulate mental images. The steps to do so are encoding, remembering, transforming, and matching spatial information [22]. Mentally reassembling orthographic displays leads to ambiguities, omissions, and interferences [30]. The Educational Testing Service (ETS) has established two tests to measure spatial cognition, the card rotation test and the cube comparison test [12]. The card rotation test measures one's ability to mentally manipulate objects two dimensionally. Each question illustrates a 2D shape and eight similar objects. Subjects must determine whether each object has only been rotated ("same") or has been flipped and rotated ("different"). The cube comparison test is similar but measures a person's three dimensional (3D) spatial cognition. Questions depict two cubes marked with a letter on each face (letters are not repeated on a single cube). If the first cube can be turned to a different position to resemble the second cube, the subject marks them as the "same". If the first cube cannot be

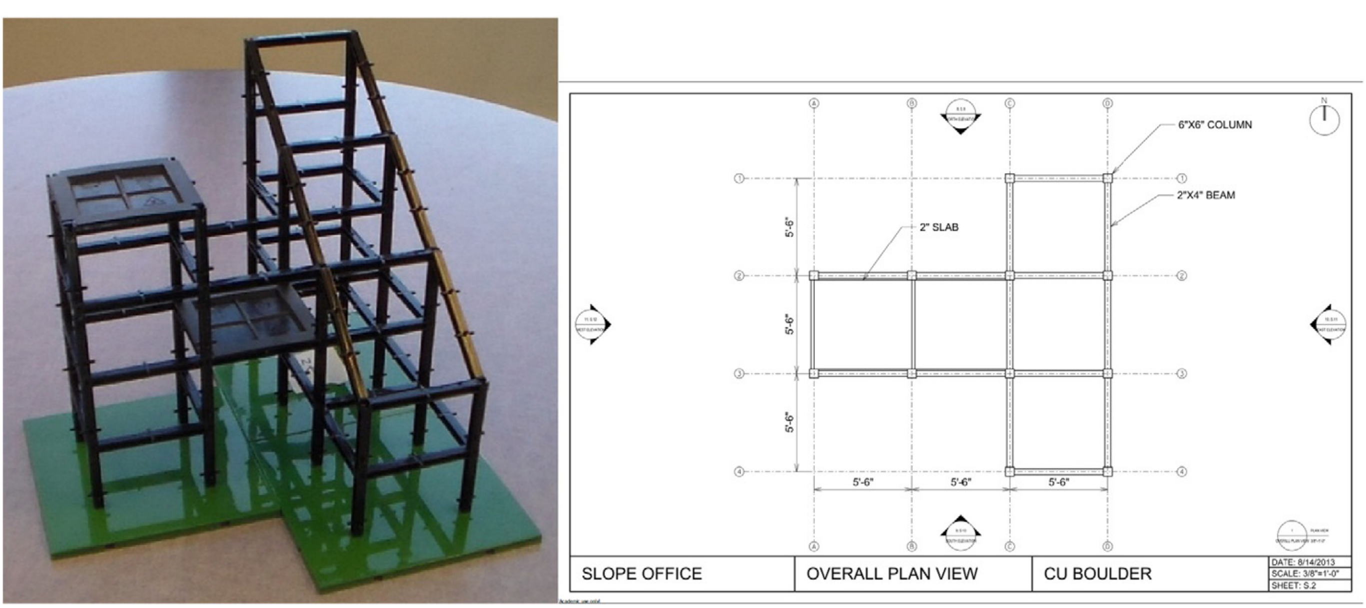

Fig. 1. Scale model Assembly 1 and 2D plan set.