Characterizing Virtual Prototype Constructability Programming for the Pictographic Instruction of Procedure

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ABSTRACT

The present design-construction information boundary is facing an unprecedented moment of self-evaluation. Global applications of building modeling - including virtual prototyping - factory-based component procurement, and industrialized site production present a combinative force poised to engulf the worn identity of traditional architecture, engineering and construction practices. Their professional facades will be inundated by a torrent of interoperability, integrative delivery methodology, and infinite informational domains. It is entirely possible that the force of this encounter could wash away the very language of traditional building culture.

To prepare, this research proposes to identify and expose the most native aspects of built-project communications. It does so by examining the architectonic relationships that exist at the foundational level of building production – that is, about its assembly tasks. A work task and its assembly procedures are investigated using the programming interface of a Virtual Prototype (VP) modeling system. The graphical characterization it suggests are tested within for the ability to translate intended design and production information into building environments that typically resist digital manufacturing applications.

The results of this investigation intend to identify a new communications format for building production. The graphical-interlingua it will suggest, may have the capacity to refresh the more insulate expressions and hollow specifications of traditional built-project design information.

ACKNOWLEDGEMENTS

Over a long-enough timeline it becomes difficult to separate the value and enjoyment derived from a goal initially attempted for its own ends.

Acknowledgements are a reflection upon those influences that kept one going. This author does so focused forward yet humbled by the insight and selfless moments offered by the following people:

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- The members of my dissertation committee, Dr. Ron Wakefield, Dr. Tanyel Bulbul, and Professor Tom Mills
- Those from the stream of faces who ultimately became good friends and teachers

I naturally reserve my deepest appreciation for my family, who by their character implicitly support the journey.

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1. INTRODUCTION

1.1 Approach

This work in its entirety suggests that the programming interface of Virtual Prototyping (VP) software can characterize constructability during its digital interpretation of design and production information. The research contribution it suggests is derived in understanding how VP constructability programming communicates to the field as pictographic instruction of procedure.

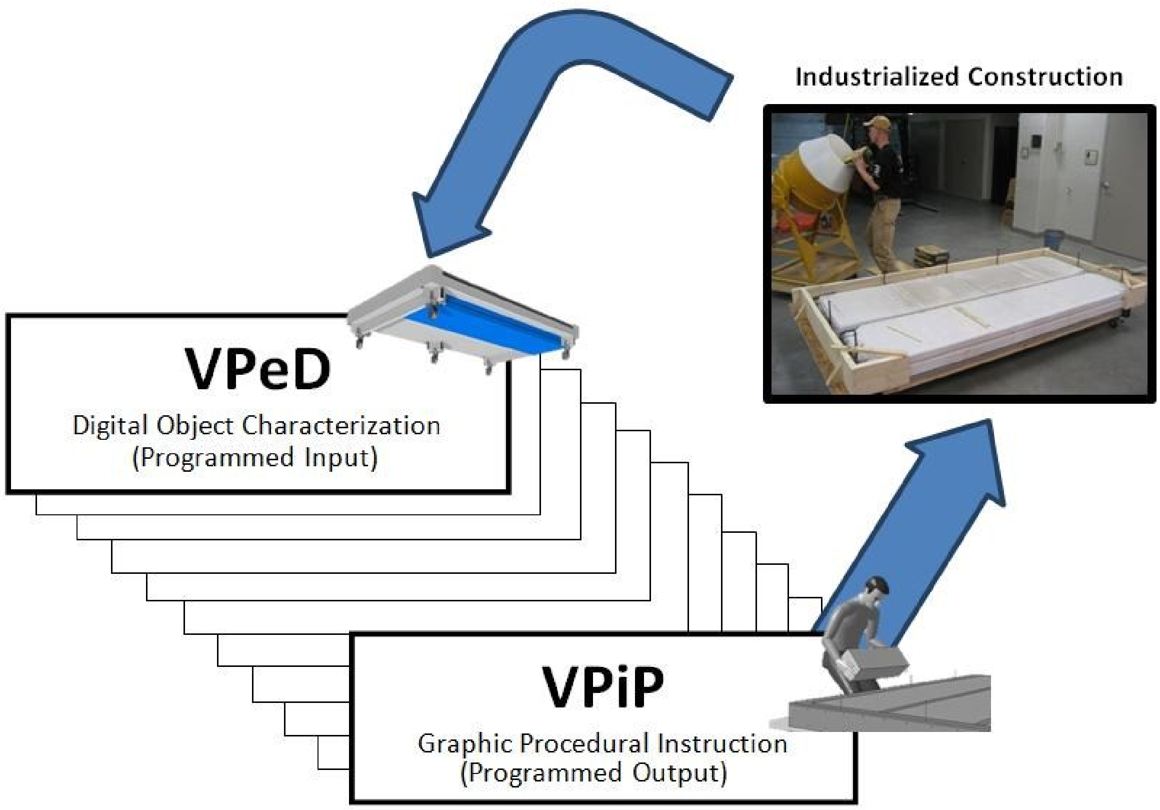

Fig. 1 The VPeD/iP Constructability Communications Cycle.

Today's virtual prototyping software offers the construction researcher rewards similar to those attained from earlier investments in discrete operations modeling (Halpin, and Riggs, 1992; Shi and AbouRizk, 1997; Halpin, 1997; Chang, 1987; Liu and Ioannou, 1992). VP's potential application to present-day production communications is a promise born from a line of thoughtful construction modeling research (Skolnick et al., 1984; Wakefield and Sears, 1997; Kamat and Martinez, 2001; Waly and Thabet, 2003).

Of that lineage, this work proposes that virtual prototyping in both a Building Information Modeling (BIM) approach and technology, enhancing design communications. Supporting research will suggest that VP's design improvement is delivered by a constructability review empowered by the programming interface. Constructability is herein defined as the completeness of a component's composite geometries and materials, assembly information and processes. This research effort examines how logically constrained representation of design information defines and communicates constructability in a small-building case study.

1.2 Paper One

This manuscript's first paper asks if VP programming can digitally characterize design and how captured geometry accounts for real-world assembly processes. The research recognizes the act of VP programming as the "primary" interface to constructability's digital definition. The resulting three-and-four dimensional (3/4D) on-screen imagery which VP and other design modeling systems communicate is understood by this research as the "secondary" interface for constructability's expression. This distinction is made to highlight how the structure of VP's programming interface translates real-world assembly issues into the digital environment. Furthermore this work suggests that the translation of design information made without a robust primary interface (e.g., professional experience or technological support) can miss production practices, even when its representation is dimensionally accurate.

Leading construction computer modeling researchers suggest that VP's power resides within its 3/4D capacity for animation (Akinci et al., 2002; de Vries and Harink, 2007). If this opinion about the secondary interface is true, what benefit then does VP modeling hold over traditional 3D plus time project modelers? Architecture, Engineering, and Construction (AEC) industry benefits associated with VP's secondary interface are reviewed in a later section of this chapter; however, this research sets to prove an alternative position held by (Cardenas, 2007) who states, "It is the digital description in the parametric model and its relation to the physical product of the designed object that is crucial for understanding how to improve the design and construction processes of the built environment." This research follows Cardenas's argument for the less-than-flashy programmatic relationship between a digital and real world.

The manuscript's first paper closes by asking, how VP constructability defined through its programming interface most effectively translates the character of primary knowledge into secondary-interface measures. With seemly contrary to the rendering power of modern design modeling, this manuscript proposes that the medium most fit to translate constructability is the two dimensional image.

1.3 Paper Two

The primary constructability knowledge derived from VPeD should benefit an end-user. The end-user in the case of this research is the person tasked with providing construction; the User Viewer Laborer (UVL). The second paper therefore asks, can a UVL's secondary interface with design information be infused with primary knowledge derived directly from VP constructability coding? To answer that question the second paper draws upon the first's development of VP Enhanced Design (VPeD), which it shows to be design information improved by VP's constructability programming. The work of the second paper then builds upon VPeD to graphically characterize VP Instructive Pictographs (VPiP). The second paper's conclusion is drawn from a test assessing the potential of VPiP communication for instructing VPeD programming.

The term modality is used frequently within this manuscript. (Moreno and Mayer, 1999) implied that graphic modality is the ability of a diagrammatic signal to manifest its intended meaning into the comprehension of a viewer. The modal capacity of still-frame and animated computer-based instruction was identified by (Rieber, 1990). The term pictograph was defined by (Houts et al., 1998) as an data diagram represented by a conceptually common picture or image. As an early cognitive scientist of the digital era, (Szlichcinski, 1984) suggested pictographs were capable of suggesting assembly procedure. A broader review of pictographic communication strategies is provided in a following section of this chapter.

1.4 Contribution

This work proposes that the programming interface of Virtual Prototyping (VP) software characterizes constructability during its digital interpretation of design and production information. Its two papers will show that the geometric constrains underlying VP constructability programming can enhance traditional design information while providing a logical script for the accurate communication of industrialized assembly procedure. The results of both papers will show VPeD/iP as an integrated contribution to design and construction research.

VPeD/iP can be understood as an inter-lingua, graphically communicating between the digital and real production environments. The benefits of VPeD/iP application are identifiable to two areas:

- AEC Project Documentation for Production Management
- Graphical Instruction Theory in Application

AEC Project Documentation for Production Management

VPeD/iP strengthens AEC insistence that modern project delivery embrace the utility, accuracy, and flexibility of digital information. VPeD is a technology approach attributable to the VP modeling classification recognized by the industry as being supportive of its present trends and goals (Lou, 2012; El Reifi and Emmitt, 2011; Eastman et al., 2011). VPiP is a lean communications approach broadening the spectrum of AEC production communications through the empowerment of its project participants (Singh et al., 2011; El Reifi and Emmitt, 2001). VPeD/iP is ndBIM supportive paradigm, encouraging both diffusion and poignant integration of AEC project information (Jorgensen, 2009; Brookfield et al., 2004).

VPeD/iP challenges present-day construction management assumptions. For example using a modern definition of lean project delivery (Ballard 2009), the pictographic approach suggested by this research refocuses project scope and work break-down concerns at the procedural level – where building are built. Its application bypasses stale hierarchies of activity and operation (Halpin and Riggs, 1992). VPeD/iP's communication of construction synthesizes project scope and the work-task into one instructive element. This integration reduces information fragmentation associated with construction project management (Bresnen and Marshall, 2001). Costly project rework would also be reduced under a VPeD/iP application, with error being less likely to reside in downstream production (Love et al., 2008).

VPeD/iP facilitates the construction manager's daily huddle – an activity synonymous with Last Planner systems (Koskela, 1992; Paez et al., 2005). Both empower the translation of lean manufacturing principles to construction's management. VPeD/iP's visual communication provides a pre-filtered, information rich signal that can be contextually familiar – an informational synergy which (Jorgensen and Emmitt, 2008) suggests eludes lean AEC project transformations. The approach advances prior research in user context integration (El Reifi, 2008), anthropomorphic analysis of construction performances (Hu and Zhang, 2011), and pre-visualization of spatial conflicts (Waly and Thabet, 2003; Hu and Zhang, 2011). The humanist benefit of a VPeD/iP approach is theorized to appease even the harsher critics of industrialized construction (Blissmas et al., 2005; McGrath-Champ and Rosewarne, 2009).

Graphical Instruction Theory in Application

VPeD/iP supports the cognitive science's understanding of how end-users receive procedural information and processes it into productive action (Watson et al. 2008). This work answers a research call from the field of Semiotics interested in the graphic communication of assembly instruction (Martin, 2007). VP pictographic instruction would support definition and instructional comprehension of procedures specification - exactly where traditional AEC production information falls short (Simon and Hayes, 1976; Clevenger et al., 2012). The visual training of labor (Koschmann et al., 1994; Mourgues et al., 2008) would be a direct benefit of virtual constructability communication. VPeD/iP is also supported by cognitive science research looking to prove that graphical instruction alone can transfer familiarity to a user-viewer operating within a complex learning environment (de Koning et al., 2010). It is reasoned that the assembly environment framed by the case-study is sufficiently complex in comparison to a modern construction site.

Finally VPeD/iP attempts to resolve cognitive science discrepancy in the value of still-verses-animated assembly graphics. While Virtual Prototyping is extremely capable of providing construction animation through its secondary interface, VPiP graphically disassembles work task simulation into its constituent parts. In doing so, it follows the lead of instructional researchers who suggest animated instruction may diminish instructional benefits. (Tversky et al., 2002). While other instructional researchers may disagree (Watson et al., 2008; Wong et al., 2009), the debate between animate and still-graphic procedural representation will only become more important as the AEC industry embraces hand-held, portable, and Augmented Reality (AR) technologies supporting BIM. The VPeD/iP approach presented within this manuscript is offered as a design communications format with the capacity to inform ndBIM technologies like augmented reality (Chen et al., 2010).

1.5 Prior Work

This manuscript is the result of a persistent but focused research effort – directed at understanding the digital character of construction's products, resources and integrative processes. In retrospect its research was a cycle analogous to the programming approach employed by any virtual prototype modeler: first, to observe and code; and second, to frame and represent. A similar ebb and flow is recognizable in the history of applied research which delivers this manuscript.

As background, this author's first research endeavor was in support of a university grant exploring how the American residential construction industry could profitably translate its custom practices into an industrialized enterprise (Wakefield et al., 2001; O'Brien et al., 2002). That effort's subsequent publications recorded the success and failures of industrial integration. During that research process, previously assumed models and terminologies became real to this researcher, such as: design for manufacturing, information exchange protocols, and discrete modeling. A study conclusion stated that, "virtual prototyping could be a mechanism for accurate representation of observed field processes, integrate field knowledge into the design process, and assist in determining the informational needs of field personal" (Wakefield and O'Brien, 2004). That charge and the experience which bore it are directly responsible for the present character of this manuscript's research

The die for further observation was cast. Dynamic field processes once attributed to wood wall framing were being replaced by systematized production. In response this researcher asked, what are the informational characteristics of panelized wall assembly? Also asked, could wall assembly protocols be captured in a virtual programming format? By these questions, the shift toward representation occurred. Virtual task representations were developed around an understanding of macro and micro-level assembly classifications (Johnston and Wakefield, 2003). (Please see Appendix document A.1)

The suggestion that industrialized field-assembly could parallel and fit the programming of virtual prototyping, required a broader investigation of that probable paradigm. The target of observation was industrialized building-material procurement within the factory itself. The semi-automated production of precast concrete foundation walls within a highly controlled environment framed new informational relationships between industrialized production and the virtual world. A resulting conference paper illustrated that virtual programming was adept at modeling the work processes encountered in a factory floor environment (Johnston et al., 2004). (Please see Appendix document A.2) This work built upon a growing realization, that VP software was more than a modeling tool. Results suggested a deeper common denominator existed between factory and field, one inherent to the software's programming structure. That realization became the next target-afield.

The logical follow-up question became how to investigate typically invisible computer coding. The answer drove this researcher once again into the production environment to observe and record the assembly routines for prefabricated foundation wall installation. That research concluded that field assembly information was substandard by every measure – especially in comparison to the efficiency and precision of BIM technology that had guided factory production of foundation walls. The field's information gap contributed to a true clash of cultures, where building products ripe with lean investment smashed headlong into a by-the-piece labor force with predictable results. From that experience, a conference paper was framed outlining alternative ways to view VP programming. It proposed an iconographic representation of the digital programming that simulates assembly observed in the field (Johnston et al., 2006). (Please see Appendix document A.3)

The icon-based assembly research suggested a fuller examination of graphical language and instructional communications. Prior work in iconographic language development was consulted – primarily from within the field of computer science, where its application was intended to enhance the user-viewer interface (Leemans, 2001; Tatomir, 2003). Further material was gleaned from the field of Semiotics. A fuller cross-section of the literature relevant to this research is reviewed below. These investigations ultimately led to a case-study which examined the present state of building material assembly-instruction. It examined the information provided with common building materials (e.g., roof shingles, residential windows, shower insert). A conference paper was delivered highlighting weakness in procedural specificity and inconsistent graphical detailing (Johnston and Beliveau, 2010). (Please See Appendix Document A.4)

That paper's finding echoed conclusions drawn from the earlier industrialization modeling. Both are summarized succinctly by the researchers Heiser and Tversky in their critical study of step-by-step assembly instruction. These cognitive scientists state, "Mechanical systems have structural organization: parts, and their relations – and functional organization: temporal, dynamic and causal processes – all explainable using text and diagrams" (Heiser and Tversky, 2005). Their interest in defining systematic assembly instruction sequences back to earlier desires for communicating the interchangeability of rifle parts in pre-revolutionary France, or the tightening of manufacturing tolerances for sewing machines and farming equipment in the latter half of the American 19th century. Names like Ford, Taylor, Gilbreth and Deming stand as monuments to a related realization, that "people are poor machines, and it is a mistake to pattern the actions of machines after the actions of people doing a similar job" (Nevins and Whitney, 1989).

Recognizing their implied challenge, this manuscript now asks how can the programmatic structure underlying industrialized construction, virtual prototype programming and graphical assembly communication, be translated to enhance labor's integration with industrialized tasks and technologies. The following two papers clearly develop a graphical approach to the characterization of assembly instruction for systematized procedural exploitation.

1.6 Supporting Research (Literature Review)

Research presented within this manuscript can be summarized as the pictographic communication of virtually prototyped constructability. Its approach graphically conveys building-model information that has been prefigured by geometric programming constraints. The resulting assembly logic from a fully developed digital prototype is represented to a user-viewer in a contextually familiar way.

While addressed within the body of each paper, the following areas of knowledge support this research effort.

- Virtual Prototyping (VP)
- Industrialization/Prefabrication
- Graphic Assembly Instruction.

Virtual Prototyping

VP is generally identified as a computer-aided design technology which supports a digital construction approach under simulated real-world conditions. This research employs a VP software suite from Dassault Systemes (Dassault, 2012). Two of the suite's main interfaces are used for this research: a geometric modeler called CATIA, and a process integration platform named DELMIA. Their seamless functionality allows a programmer to accurately define a construction product as a component composed of smaller parts in sub-assembly. The addition of anthropomorphic assessment tools and sequential part pathing allows for a geometrically accurate representation of construction activity.

VP applications were initially developed and extensively tested within the automobile and aerospace manufacturing sectors (Choi and Chan, 2004). VP's earliest AEC industry applications were suggested for mechanical engineering analysis (Pratt, 1995; Harrison et al., 2001). VP models have been applied to model construction operational environments

(Xiang et al., 2004; Tawfik and Fernando, 2001). VP has been suggested for the development of work specification (Shen et al., 2005). VP was used to model the project management of high-rise construction (Riese, 2008). Bargstadt and Blickling (2005) suggested VP for examining process durations.

Gou (2009) suggested that VP offers an ideal platform for testing production processes geared toward industrializing construction. The effect insufficient design information has on real-world prototyping has also been studied (Akintoye et al., 2000). Li et al. (2011) suggested a VP approach toward the geometric optimization of design – akin to flat-pack manufacturing. Their application of VP technology to the prefabrication and installation of precast building components showed the technology's capacity for time saving and safety improvement.

VP has been suggested as a multi-domain Building Information Modeling (ndBIM) tool (Aouad et al., 2005). VP was evaluated by (Park and Peña-Mora, 2003) as a ndBIM technology lowering the possibility of design error, rate of rework, change orders and overall construction schedule disturbances. VP's ability to support lean production methodologies and construction project integration has been examined (Halpin and Kueckmann, 2002; Huang et al., 2007). Sarshar and Christiansson (2004) offered a VP workspace to simulate lighting, acoustics, energy consumption and safety modeling considerations. Virtual prototyping has been suggested as an ideal tool to model the lifecycle assessment of buildings (Li et al., 2008).

Industrialized Building Environment: Supporting Research

A definitive characterization of industrialization within the construction industry is challenging. The term may be better understood by the uncertainties, interdependencies, and inefficiencies of operations which industrialization attempts to systematize (Dubois, 2002). Modern AEC industrialization efforts address the dynamic influence of on and off-site forces (Eastman and Sacks, 2008.; Lu, 2009). Prefabrication and pre-assembly are common procurement and material delivery theories associated with industrialization (Gibb, 2001). A manufacturing approach to delivering construction is now a global phenomenon (Lou and Kamar, 2012).

The AEC has a relatively modern interested in applying perceived time and cost saving of industrialization to construction (Koskela, 1992). That interest has been associated with building quality improvement (McKone et al., 2001) and increased safety standards (Tam et al., 2007). Prefabrication's positive effects on large construction site productivity has been measured (Chiang et al., 2005). Industrialization's impact in larger construction environments has been critiqued (Gibb, 2001). Residential construction efforts seeking flexible and integrated manufacturing approaches have also been studied (O'Brien et al., 2002).

Criticism of industrialization in construction has keyed on design incongruence with off-site manufacturing and a the degradation of onsite worker skill sets (Blissmas et al., 2005). It is further suggest by McGrath-Champ and Rosewarne (2009) that a de-skilled labor force faces an industrialized production environment that further challenges worker safety and effectiveness. McKone, Schroeder and Cua (2001) foresaw a need for training performance management in relationship to lean production avenues desired by the AEC. Many solution sets suggested for fixing industrialization shortfalls rely on traditional production scheduling and resource optimization at the factory level. Vera et al., (2009) saw VP as the ideal tool for reaching deep into the premanufactured building supply chain. Thomas and Sanvido (2000) suggested ineffective labor-driven processes matched with premanufactured products drove onsite production errors. Phua (2004) called for reevaluation and engagement of the operational culture which deliver industrializing construction. Watkins et al., (2009) also offered that it was essential to recognize labor's work contribution in context with an industrialized building environment

Graphic Instruction and Assembly Communication Research

This research is supported by the communicative power of the Pictograph. Pictographs differ from icons (Leemans, 2001; Tatomir, 2003), in that their visual character is defined by a practical representation of the object or action being rendered (Bertoni et al., 1991). Pictographs can range from simple line drawings to photorealistic pictorial representations. The field of cognitive science has developed theory linking text and diagrams with learning (Booher 1975; Beiger 1982). Szlichcinski (1984) offered a modern design-interpretation of pictographic communication. The cognitive-science researchers (Ellis et al., 1996) promoted the pictograph's potential for qualitative task instruction. Pictographic instruction has been found to be an effective graphic medium for explaining medical instructions and boosting a user-viewer's procedural recall of them (Houts et al., 1998). Morrow et al., (2004) validated pictographic procedural instruction and recall enhancement findings. (Kools et al., 2006; Zeng-Treitler et al., 2008) both associated pictographs with aiding a user-viewers definition of mental models – a key psychological tool supporting the comprehension of procedural task instruction.

More recent cognitive science literature establishes that humans can infer motion and physical force from still-frame graphics (Mayer, 2010; Toskos and Boroditsky, 2010). Cognitive researchers have also found still-frame cues can indicate directionality and time (Ellis et al., 1996; Krull and Sharp, 2006; Heiser and Tversky, 2005). Paas et al., (2003) showed the effects of graphical clutter could be associated to cognitive overload.

The static-graphic instruction approach suggested by this paper is supported by cognitive science research in sequenced 2D assembly graphics (Agrawala et al., 2003). Tversky, et al., (2002) suggested that still-graphic instructional cues are just as effective as animation in assembly communication. Watson et al., (2008) however identified assembly animations as producing faster 'first-build' times over still-frame graphics. Martin (2007) work showed that a user's comprehension of procedural instruction benefits from graphic presentation rules applicable to pictures and diagrams.

1.7 Problem Statement

The key research questions posed by this manuscript are presented as follows:

1) Does design information formatted into the hierarchy of Virtual Prototype programming exhibit measurable evidence of constructability enhancement?
2) Can the primary constructability information in VP Enhanced Design (VPeD) be characterized for non-verbal translation to a secondary user-viewer?
3) Does the VP instructive Pictograph (VPIP) affect a measurable modality for a UVL working in an industrialized construction environment?

1.8 Methodology

Specific research methodology applied to case-study is further defined within the body of each paper included within this manuscript; however, Figures Two and Three shown below succinctly characterize both investigative approaches.

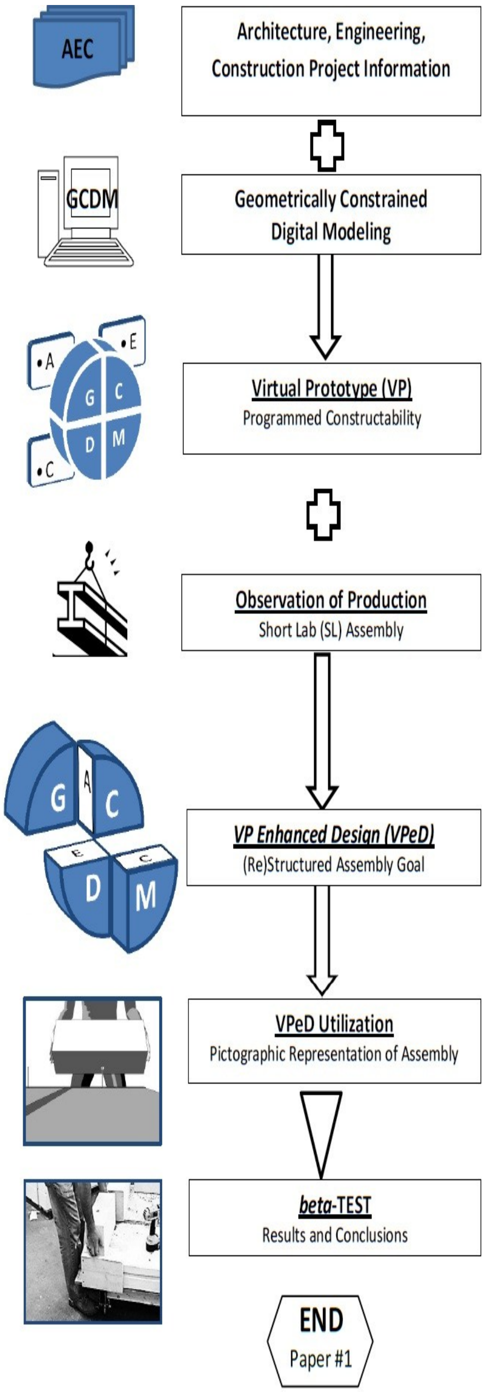

Fig. 2 Paper One VPeD Development Path

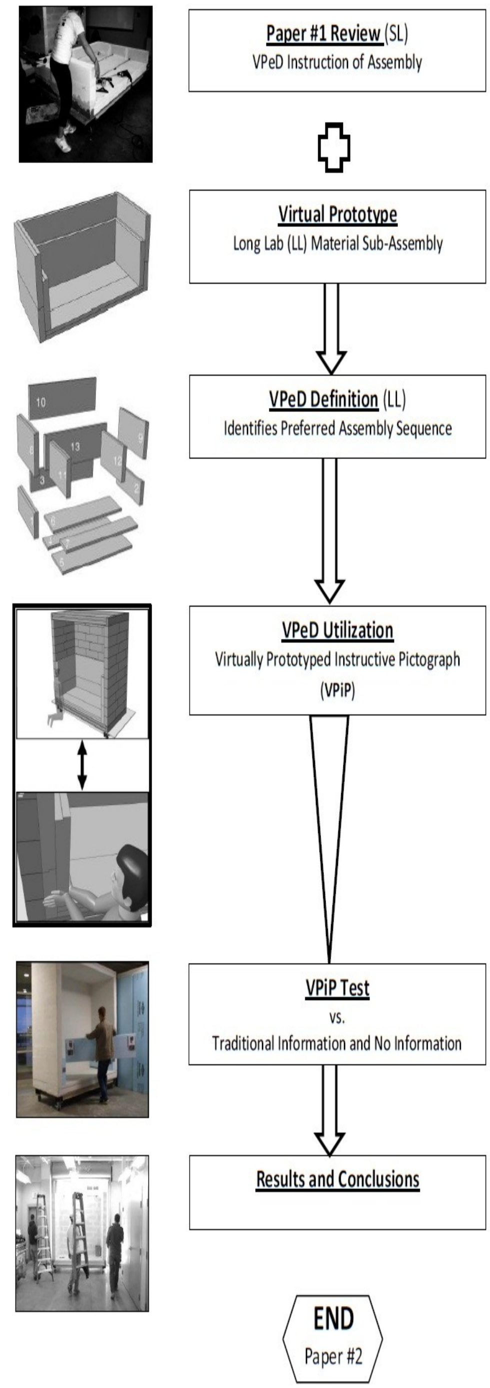

Fig. 3 Paper Two VPiP Development Path

2. MANUSCRIPT 1

2.1 Virtual-Prototype Enhanced Design (VPeD) for Constructability Communication

2.2 Abstract

This research develops a communications relationship between intended design information and actual building production. Its study highlights how the programming interface of a Virtual Prototype (VP) modeler addresses the integration of project design information, assembly specifications, construction materials, means and methods. VP's constraint-based programming is suggested as a digital link to constructability review and design enhancement – or VPeD. VPeD is shown to enrich traditional design information in a building case study. The work highlights VP capacity to translate the specificity of its modeling into instructive imagery that is contextually useful to project participants.

2.3 Introduction

This research approaches Virtual Prototyping (VP) as both constructability analysis and communicator of production's means and methods. In focus, is a case-study involving the real-world production of a 'Building Envelope Systems Technology' mobile laboratory (Lab). Project documentation along with construction assembly observations provides data for a virtual review of the Lab's assembly. The structure was to be assembled by novice university student-labor utilizing industrialized building materials in an indoor environment. As such, the project presented a unique research opportunity for examination of its constructability and graphical instruction.

2.4 Virtual Prototyping

The virtual prototype, like its real-world counterpart, is ultimately a model. Prototypes are used to evaluate physical form and design concepts, performance characteristics and manufacturability prior to, or in lieu of building a real-world product (Dai and Göbel, 1994). The virtual prototype has been defined as, "a computer simulation of a physical

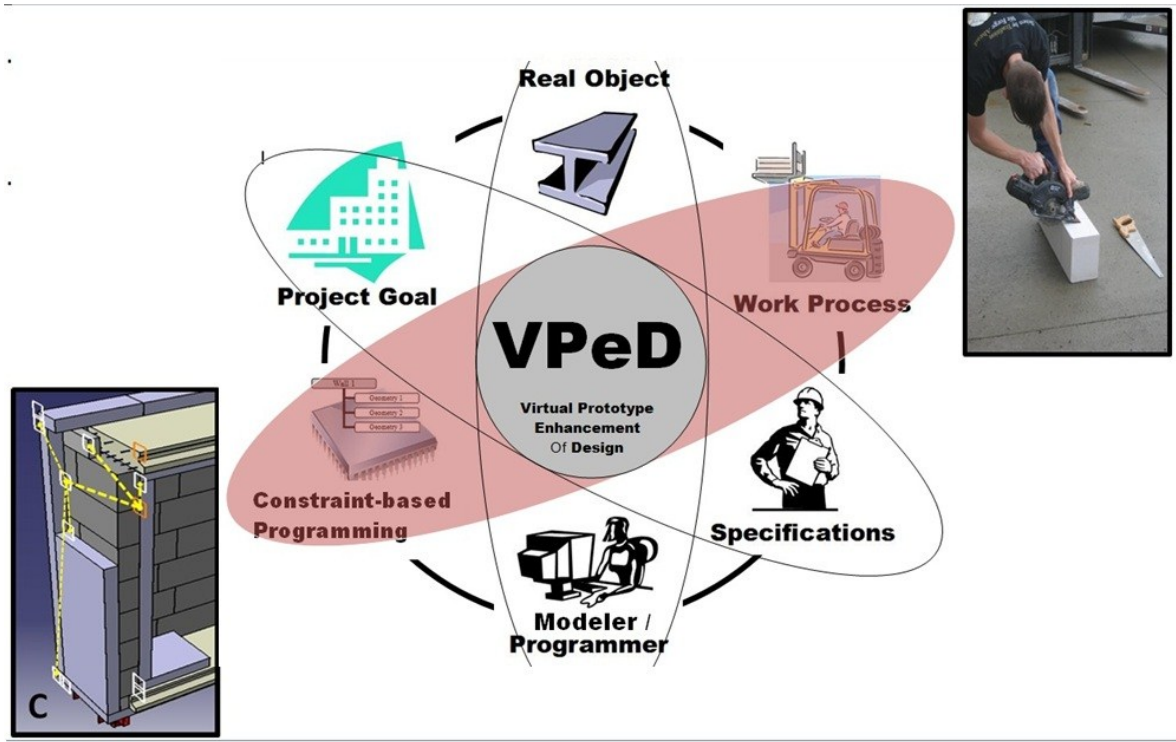

Fig. 4 Information Domains Contributing to VPeD Constructability Programming

product, where it's digital programming and testing are called virtual prototyping (VP)" (Wang and Yang, 2011). Virtual Prototyping is gaining recognition within the Architecture Engineering and Construction (AEC) industry (Harrison, 2001). That industry wishes to utilize VP's capacity to digitally represent built-products (Harrison, 2001; Gou, 2009; Heng et al., 2011) and encourage integrated project delivery (Dawood et al., 2003; Huang et al., 2007; Hu and Zhang, 2011).

This research recognizes AEC design document development as in iterative process, increasing design detail from the conceptual to schematic, through to production drawing. Virtual prototyping informs in an alternate direction – communicating detail from a completed digital model. Conceding the time, effort and informational investments that formulate a virtual prototype, it component model can be understood as possessing imbedded assembly information. When VP presents information to the field, its expression could be seen as immediately deductive in nature. This is opposed to traditional design documentation which typically requires a user-viewer to dig further into the drawing package to acquire finer production detail.

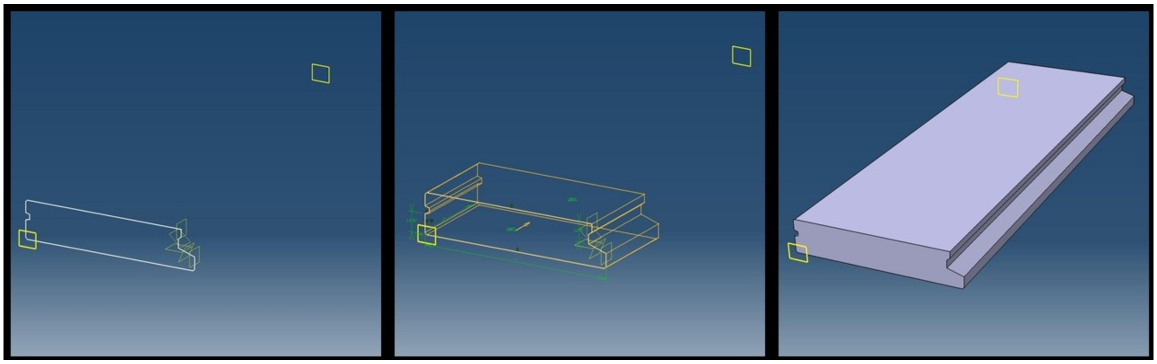

Fig. 5 VP Programmer Constrains Geometry of a Virtual Object

In consideration of the above argument, this research asks what is the character of constructability knowledge programmed within a virtual prototype's component model, and how might it be most effectively communicated to the field without the use of traditional instructional media or mediums?

This paper sees virtual prototyping is a balance between geometric constraints of the programming interface and real-world constraints found within the actual construction environment. Figure four illustrates these two contributors to VP's constructability programming. This paper will show how their digital relationship within a constructability review can be understood as Virtual Prototype Enhancement of Design (VPeD).

Digital Geometric Constraints

Virtual prototype programming (i.e., virtual prototyping) was defined by (Song and AbouRizk, 2006) as a technologic capacity to simulate a user, the product, and their combined interaction

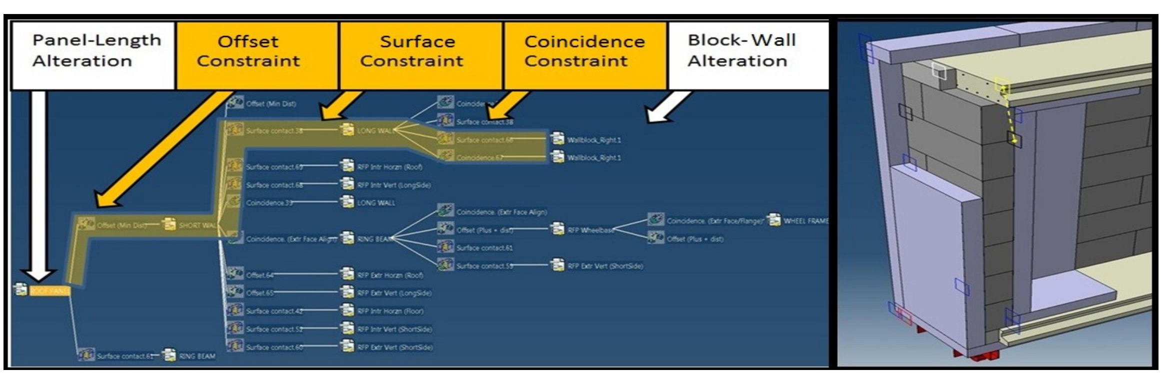

Fig. 6 Programming Constraints Establish 3D Object Cohesiveness and Parametricity

Fig. 7 Design-Engineer Specified Panel Alteration

within a software. Virtual prototyping requires a modeler to set geometric constraints defining the digital object which populates the virtual environment (See Figure 5). Geometric constraints are the foundation of virtual prototyping and their programming is what empowers parametric functionality (Cardenas, 2007). Geometric constraints can be manipulated at any time within the model or scripted via computer coding. VP constraint programming also defines the geometric associations of aggregated parts within a larger component model (See fig 6). The component model is synonymous with the digital product model, both concepts derive from the manufacturing industry's early application of VP software (D'Adderio, 2001). Creation of the component model is considered the primary functional step in virtual prototyping (Choi and Chan, 2004). This research employs two related software from Dassault Systemes, to build and analyze a VP component model: CATIA and DELMIA (Dassault, 2012).

Real Process Constraints

The logical constraints inherent to construction operations are well known in the

Fig. 8 ACC Prefabricated Panel (Object)

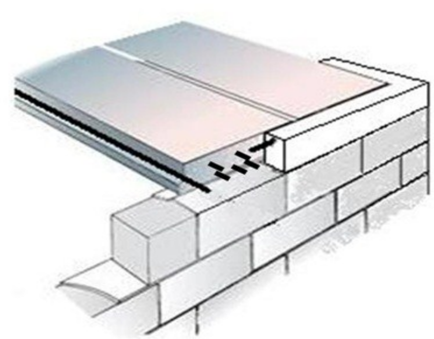

Fig. 9 Project Goal (Researcher Rendering)

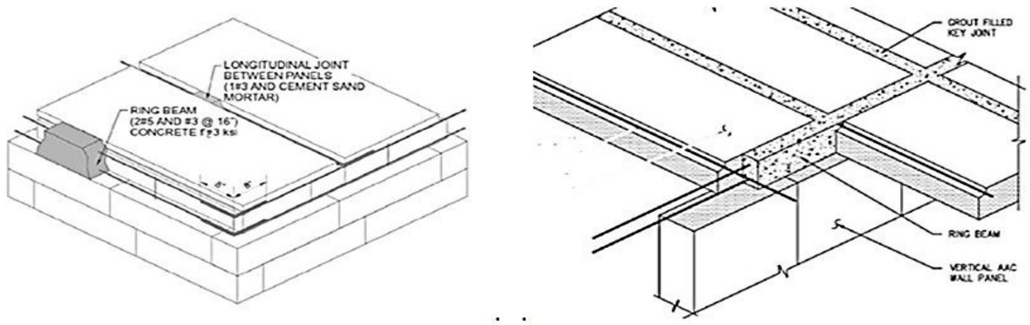

Fig. 10 Construction Drawings Do Not Recognize Panel-Face Field Alteration

chronicles of construction's modeling (Halpin, 1977; Chang, 1987; Skolnick et al., 1990; Liu and Ioannou, 1992; Martinez, 1996; Wakefield and Sears, 1997; Koo and Fischer, 2000). However, the discrete modeling of construction's finer activities has resisted digital representation (Kamat and Martinez, 2002). Figure 7 is shown to illustrate how the in-situ construction environment at a micro-level of operational activity becomes an important contributor to down-stream constructability. The figure's images reflect production activities that were directly determined by the design engineer's assembly specifications. A full-sized *Autoclaved Aerated Concrete (AAC)* panel and this author's representation of the intended panel-to-wall assembly connection are shown in Figures 8 and 9.

The importance of assembly representation in VPeD constructability modeling began with Industrial System's science and its early characterization of the logical ordering that occurs in physically sequenced parts of an assembly (Frommherz and Hornberger, 1988; Homem de Mello and Sanderson, 1990). Modern VP reflects the manufacturer's concern

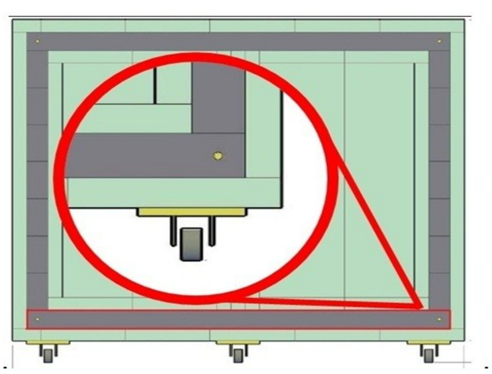

Fig. 11 First Digital Model (Schematic)

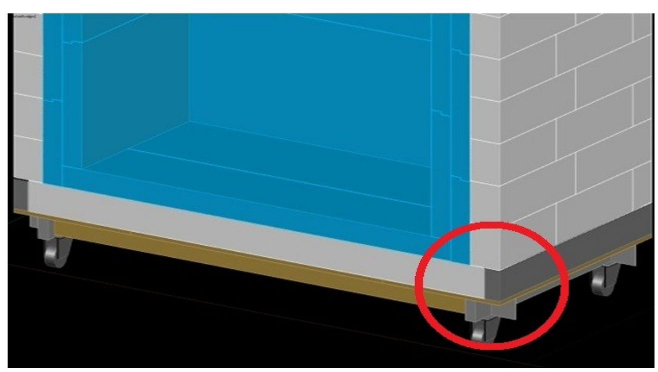

Fig. 12 Second Digital Model (Detailed Design)

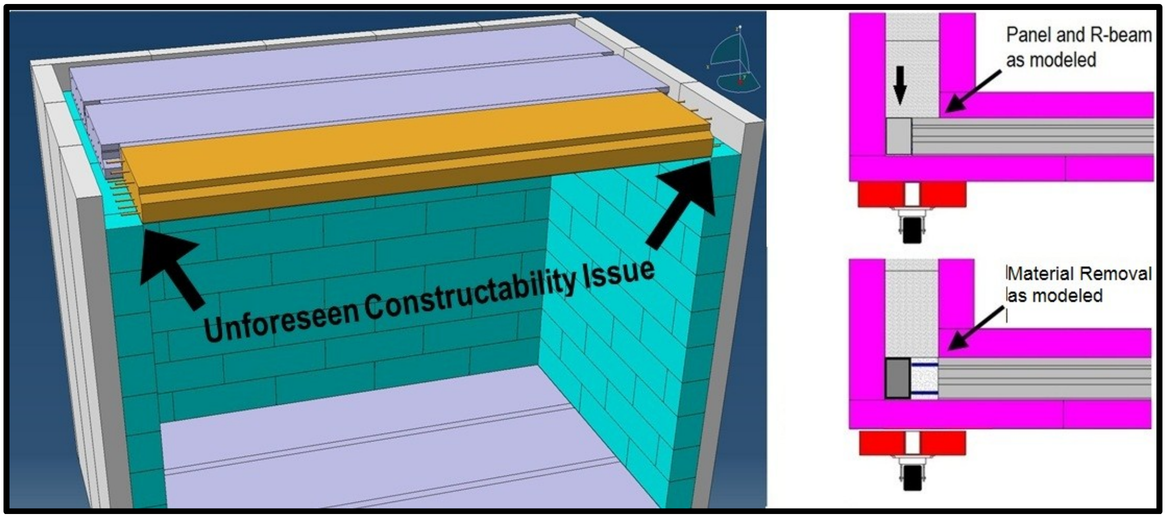

Fig. 13 VP Identifies Embedded Constructability Challenge in Prior Project Modeling

for the smallest assemblies through geometric constraint programming. This accounting may best be understood through VP's capacity to exploit sequenced disassembly. Disassembly is a key representational tool behind 4D modeling (Dumisevic et al., 2003; Wang and Yang 2011; Li et al., 2012). Some researchers have suggested disassembly programming is a form of construability review (Bargstadt and Blickling, 2005; Li et al., 2009). The conceptual strength identified with (de)construction representation is exactly what still-graphic AEC construction documentation attempts to detail in Figure 10. The AAC material vendor communicates the creation of a concrete ring / bond-beam in

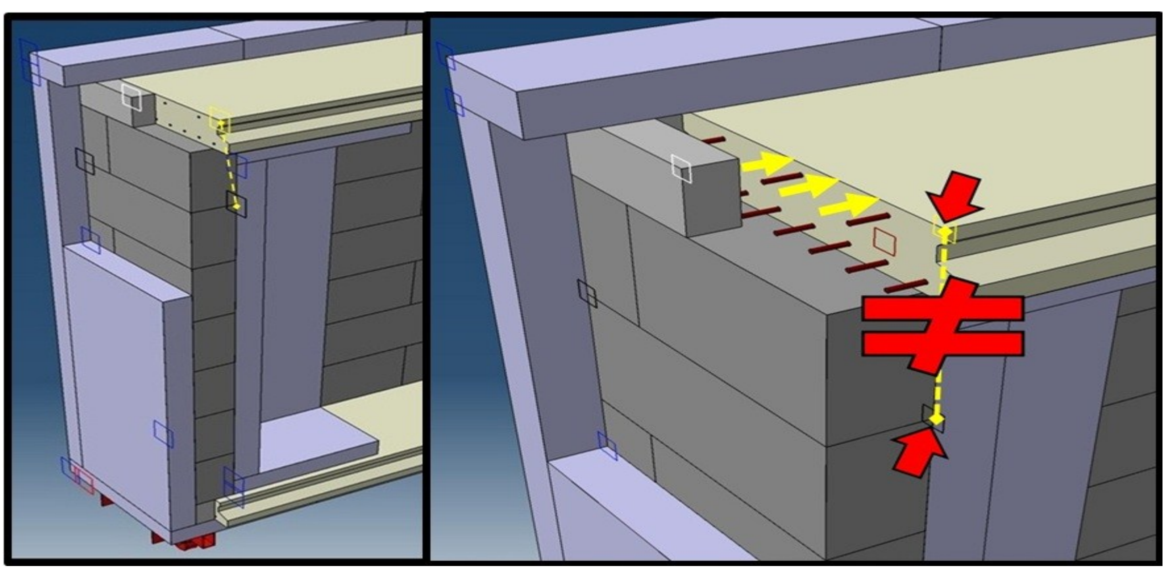
Fig. 14 VP Constraint Programming Forbids Material Planes to Meet

Figure Ten. Both of its drawings capture ring beam assembly detail as defined during the Lab's iterative digital modeling process. Figure 11 illustrates the poured ring-beam in correct relationship to the Lab's finished dimensions. Figure 12 also correctly represents the Lab's finished dimensions, yet characterizes its assembled parts with a higher-level of component detailing. What is not communicated by drawing or digital modeling is a hidden downstream production issue caused by the DE's intended design modification. Figure 13 employs VP to illustrate how the hidden production issue impacts the Lab's downstream structural performance and in-situ constructability.

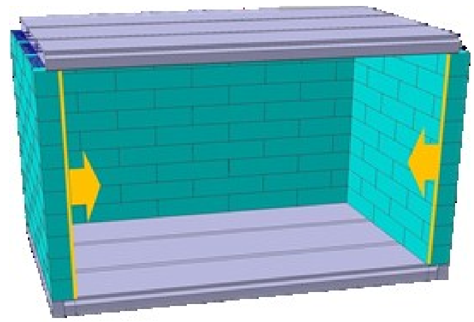

Fig. 15 VP Suggested Wall Translation

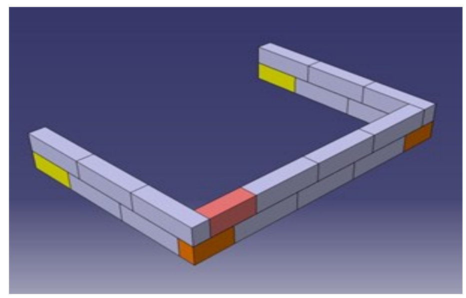

Fig. 16 Resulting Block Pattern Shift (LL)

If the Lab was constructed to vendor drawing specification or project modeling, the AAC wall blocks could not have rested upon the AAC floor panel. Similarly, the panel material removal called for by the design engineer would have ultimately required temporary-structures inside in the lab to facilitate roof panel positioning during the upper ring-beam pour.

Fig.17 Observation of First Build (SL)

This paper recognizes that an experienced designer modeler and/or construction engineer may have caught this representational discrepancy. However, it is equally as likely that an inexperienced project participant would have let the lack of detail go to the field, where it

Fig.18 Bi-directional Work (SL)

would have manifested itself as a real-time constructability challenge. What is certain is that the VP programming interface encourages modelers to associate the key geometries of all digital parts encountered within the virtual component.

Figure 14 represents a constraint relationship between the block wall and the panel's face, as established by a VP programmer. When digital constraint tools such as offsets and anchors are properly configured, the digital planes carrying the respective wall and panel geometries are prohibited from becoming coplanar. At a bare minimum the VP modeler is forced to conceptualize such conflicts when digitally associating objects in their final assembly representation.

When digital constraints are programmed by an expert modeler, a VP can achieve parametricity. This means, that as a VP programmer replicates the design engineer's assembly specifications the model can adjust part and component geometries to facilitate their connection. Figure 15 suggests a component-level parametric solution to the constructability conflict suggested above. Figure 16 illustrates the design engineer's new block layout scheme predicated on a parametric wall translation. The new wall-course layout is VPeD.

Fig. 19 Labor Procedure Preference (SL)

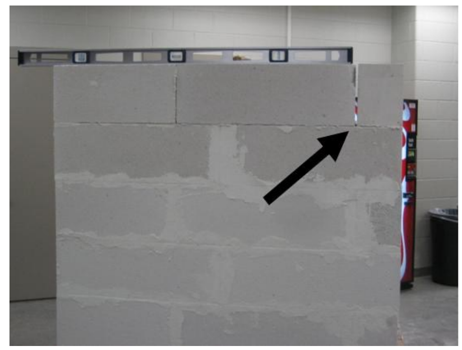

Fig. 20 Procedural Error Compounded (SL)

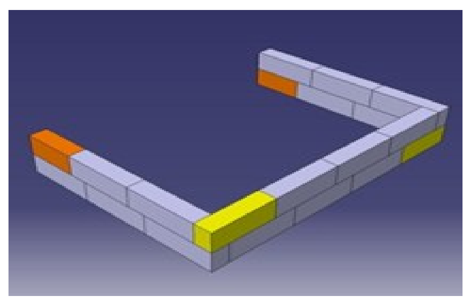

Fig. 21 VPeD Adjusted Block-Pattern (LL)

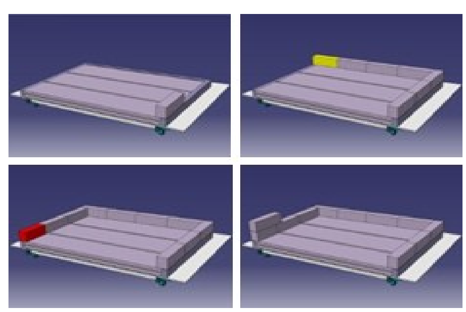

Fig. 22 Adjusted Production Scheme (LL)

2.5 Site Production Observations

Short Lab Case Study

The assembly project reviewed by this study is a mobile test chamber intended for building envelope performance research. The Lab has three primary components: two opposing mechanical spaces and a removable center wall section – the latter part is not considered within the scope of this study. The smaller of the two sections – or Short Lab (SL), is the initial focus of this study.

The general materials list for Lab construction included: solid AAC structural wall blocks, reinforced AAC floor/ roof-spanning panels, ridged Styrofoam insulation panels, and a customized metal wheel-frame. A small amount of cement mortar and reinforcing steel rod was also included. The construction methodology envisioned for the project was specified by an acting design engineer in consultation with the aerated-concrete building systems supplier.

Short Lab (SL) Production

Wall production presented a case where operational activity was under-informed by available production information. AAC block assembly was not actively directed by an onsite construction manager. Laborers were left to interpret wall-assembly from available paper-based and digital model information. Figure 17 illustrates labor pre-staging materials prior to assembly and suggests distrust in provided production materials. Figure 18 illustrates two laborers working simultaneously at opposite ends of the same wall course. Figure 19 illustrates labor's observed preference to place the first block of each new course at wall's end. This operation provided the maximum number of lower-block faces from which to square and plumb; however, Figure 20 shows the downstream assembly error which frequently arose from this practice. Corner gaps occurred due to the fact that production information indicated end-blocks were to be cut. Labor's inability to maintain material tolerances and bi-directional work compounded with the preference to begin assembly at wall ends. To inexperienced, unguided labor the corner joint error is an unforeseen but predetermined outcome of error propagation and low fidelity procedural specification.

In the case of SL production the provided design information did not adequately match labor's level of experience or its natural affinity for processes like end wall starts. When these factors were combined with poor production tolerances and bi-directional work the assembly quality fell and rework increased.

SL Impacts on Long Lab VP

Figures 21 illustrates a VPeD adjusted production plan based on the constructability issues identified in SL assembly observation. The VP programmer had the ability to alter the upcoming construction of the Long Lab (LL). In particular, changes were allowed by the design engineer to the AAC block positioning within the wall courses. VP programming allowed for the consideration of labor's domain tendencies observed within the Short Lab construction scenario.

The VP software's object-based environment allows the programmer to graphically reconfigure the Long Lab's original block wall design - integrating those production protocols oberved to be useful. Figure 21 illustrates a reconsidered VPeD assembly sequence addressing:

1. fewer number of cut blocks
2. reduced number of block-cut types
3. isolated cuts to wall corners and ends, where cut tolerance anomalies can be mitigated
4. a linear and repetitive (by reverse course) assembly sequence that always began at preferred wall-ends

2.6 VPeD Instructional Theory

This research proposes that graphics-only instruction formatted directly from a VPeD model can overcome a worker's procedural bias through VP enhanced instruction

The instructional theory portion of this paper builds upon the following premises:

1. Real-world production (assembly parts and processes) can be digitally characterized and optimized using VP

2. Labor's familiarity with work's procedures and specifications (i.e., protocols) is a form of cognitive bias influencing their mental model of assembly (Brunyé et al., 2006; Höffler and Leutner, 2007)
3. Mental models can be altered by appropriate graphic images and cues. (Ellis et al., 1996; Haijiang et al., 2006; Winawera et al., 2008)
4. Graphical cues derived directly from the VPeD modeling environment can support and enhance in-situ work instruction. (Martin, 2007; Watson et al., 2008)

To test the above points, this paper proposed a beta-test where workers would be graphically instructed (i.e., non-verbally) along the Long Lab's VPeD adjusted wall block assembly path. Production tasks would be exactly similar to those they had performed during the Short Lab's wall assembly, except for the abovementioned changes highlighted in sequence by Figure 22. The same labor force would be used for LL wall production to ensure their prior experience acted as a cognitive bias against which to benchmark VPeD's instructional communication as modal.

Characterizing VP Task Protocols

Before a beta-test of VPeD instruction could be administered, the graphical character of that instruction had to be assessed. Research pointed to the instructional effectiveness of still-frame visual cues. Researchers suggest still-frame

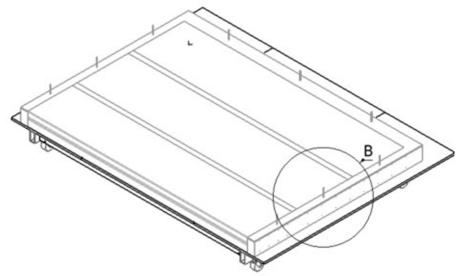

Fig. 23 Axonometric Task Location

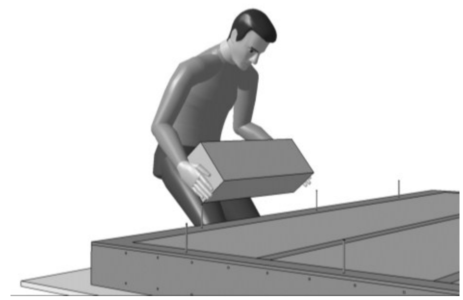
Fig. 24 3d Perspective Task Location

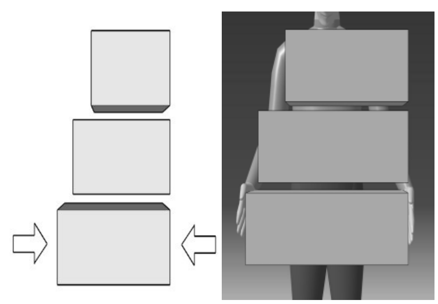
Fig. 25 Anthropomorphic Part Cues

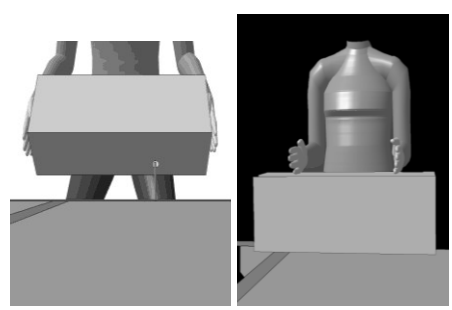
Fig. 26 Start and End-Task Cues

graphics convey processes as effectively as animation (Tversky et al., 2002; de Koning et al., 2010). Thus investigation began to develop still-frame cues which defined work protocols directly from the VPeD programming of the LL's production. For example, Figures 23 and 24 illustrate alternative visual approaches to a block's assembly location. Both frames are derived directly from the VPeD model, yet visually cue part positioning differently relative to the deck's sub-assembly.

It was hypothesized that the representation of tools and building materials could receive a stand-alone visual cueing. Cognitive science research suggested that ideographic cues can signal differentiation in materials or objects to a user-viewer (Wickens, 1991). This research attempted to separate itself from other visual cueing approaches which rely heavily on 4D modeling. It does so by purposely handicapping composite visual cues common to 4D time-sequenced animations (Koo and Fischer, 2000; Sampaio and Santos, 2011). Only resource-to-resource integrations are visualized. This is done to clear the limited display space of unnecessary information. Instructional research suggests that complex and/or compound geometric cues may limit a viewer's comprehension through cognitive overloading (Ayres and Paas, 2007; Arguel and Jamet, 2009). It was theorized that VPeD instruction could be scripted in conjunction with a

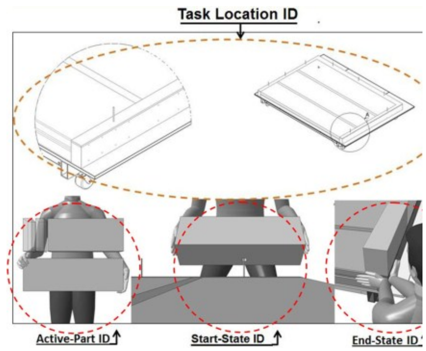

Fig. **27** Composite Pictograph

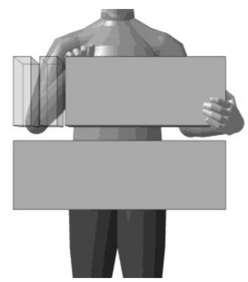
Fig. 28 "Cut- Material" Hybrid Cue


Fig. 29 Uni-directional Assembly (LL)


Fig.30 VPeD 2nd Course Start (LL)

systematic ordering of real-world materials at the resource pile. Thus the need to identify particular materials was a primary concern of the research (See Figure 25).

A similar visual shortcut was applied to the expression of work procedure. For the LL's beta-test, numerous sub-tasks which support AAC block-assembly were omitted (e.g. cutting, drilling, mortaring, and leveling). As beta-test subjects had recently completed the short lab's wall assembly; previously understood tasks could be ensured by a verbal reminder to employ all necessary means and methods applied to the prior wall assembly. Using this approach, visual cueing could focus on the graphical development of a single work process. Figure 26 illustrates two still-graphic options for expressing the block-delivery activity.

Composite Pictographs

Figure 27 illustrates a composite presentation format chosen to express AAC block installation. Its four protocol windows combine to form one composite pictograph (Szlichcinski, 1984). The larger task location window opted for a more traditional axonometric line drawing with circular graphic callout. The beta-test developer felt that this image was as informative as the more robust anthropomorphic alternative. Its scene cleanly signaled the task's location supported by a canonical point-of-view deemed effective for procedural cue illustration (Krull and Sharp, 2006).

The active-part window illustrated building materials 'in-use' during the assembly activity. Figure 28 shows a hybrid image that was proposed to cue alternative block-types. The figure uses anthropomorphic cues to alternative block sizes. This choice to cue the active part with an abstract graphical representation proved to be problematic during beta-testing.

'Start-State and 'End-State' images were intended to convey the bulk of the task's information. Still graphics can present a challenge to the portrayal of sequential activity (Wong et al., 2009). This research agreed with (Schwan and Garsoffky, 2004) in their belief that a user/viewer can conceptually bridge limited omissions in the portrayal of a sequenced activity. Their suggestion is further supported by work on well-framed activity (Krull and Sharp, 2006). The resulting two windows work in conjunction to provide a clear 'before and after' representation of the intended procedure. Both windows employed anthropomorphic hand placements as directive visual codes (Kools et al., 2006).

2.7 Instructional Beta-Test (Long Lab)

The goals for the field test were defined as follows:

1) Identify if Labor can recognize and be informed by VPeD graphics without verbal instruction
2) Can pictographic comprehension overcome a worker's procedural bias acquired from the Short Lab construction (e.g., leading them along the new assembly path)

Methodology

Four participants were chosen at random to install 20 AAC blocks along the first two courses of the Long Lab. Test subjects were told to follow the pictographic instruction set, applying all relevant means and methods necessary for block assembly – as they experienced in the previous Short Lab assembly. A secondary laborer pool was made available to each test subject. Secondary workers were limited to assisting subroutines (e.g., cut block, mix and apply mortar). Each test subject received one composite pictograph pre-order by the VPeD determined assembly sequence. Test subjects and helpers were randomly reselected upon the completion of each block's assembly. The test continued until both courses where completed.

2.8 Results

All twenty blocks were correctly placed along the first two courses of the Long Lab. All test subjects followed their pictographic instruction along the new assembly sequence defined by VPeD. Uni-directional block work was enforced (See Figure 29). Bi-directional work was eliminated. All cut-blocks occurred at a wall's terminating corner or end.

Figure 30 suggests the instructional effectiveness of composite pictographs derived from VPeD programming. The image highlights the first assembly of the second course. Its laborer was able to deliver a cut part into its proper assembly location, without the aid of verbal instruction or other project information materials. In doing so, the worker ensured a proper linear progression of the mirrored assembly sequence identified as most efficient by VPeD. Continuation of the VPeD assembly sequence could be expected for all subsequent block courses.

2.9 Conclusions

This paper has illustrated that the geometric assembly constraint programming required by virtual prototyping, is an effective constructability review when applied to AEC building information. This research also shows how the software interface used to program a virtual constructability review can be pictographically scripted into an instructive communications format – one capable of cueing workers along an optimized assembly sequence. The application of VP enhanced design to instructive communications is an idea supported by existing cognitive science research. The suitability of that application is strengthened by these findings which suggest pictographic communication is an appropriate method for cueing human comprehension in a construction work task.

This research has pointed out some initial limitations to the modality of pictographic task instruction. Modality is defined within this paper as a signal's capacity to manifest its message correctly within a viewer. A primary hurdle is seen in the amount of time and effort a VP modeler must spend translating real-world production protocols into virtual programming schemes. A secondary hurdle is seen in the development of effective graphical frames which convey the intended instructional signal. This directorial challenge was seen specifically in the researcher's choice of a hybrid image for suggesting cut-blocks in the Active Part ID window. One beta-test participant could not continue with the task until the test's proctor verbally communicated the images exact meaning. In a post-study review one participant responded that they had initially interpreted the image to mean two-blocks were to be carried.

In summary, VPeD's programmed expressions of constructability can have a real impact on design review, worker training and task communications. Development of VP's inherent ability to communicate prefigured design-production information in a format which is familiar to the domain of labor is a challenge worth further consideration.

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3. MANUSCRIPT 2

3.1 A Procedural Assessment of Pictographic Assembly Instruction Derived from Virtual Prototype Modeling

3.2 Abstract

This research formulates a test of pictographic instruction for construction assembly procedure. It employs Industry-recognized virtual prototyping (VP) software to 3D model the assembly configuration of Styrofoam panels insulating a mobile test laboratory. (A fuller examination of VP enhancement and still-graphic communication of the Lab's design is addressed in an earlier paper by this author.) This paper further develops the idea that 3D imagery resulting from VP constructability programming can be used to characterize instructive pictographs to non-verbally guide a user-viewer laborer (UVL) toward prefigured assembly solutions. This research builds upon prior cognitive science research in graphic communications and assembly instruction. Test results speak to Virtual Prototyping as a ndBIM technology with the capacity to better integrate AEC project delivery with user-specific domain knowledge.

3.3 Introduction

This paper benchmarks a level of efficacy in non-verbal assembly instruction while guiding industrialized building procedures. Its work is based upon prior findings by this author in development of a Virtual Prototyping approach to Enhanced Design (VPeD). Previous research highlighted the geometric constraint programming required for virtual constructability modeling of a mobile laboratory (See Figure 31). That work illustrated VP programming to be an appropriate descriptor of protocols defining real-world assembly procedure. The research proposed an instructive communications beta-test using virtual pictographs derived directly from the programmatic scripting of constructability. Initial results suggested promise in guiding real-world labor along an assembly sequence characterized by VP enhanced design programming.

This paper proposes a more rigorous test of Virtual Prototyped Instructional Pictographs (VPiP) to better understand their suggested communications efficacy. Its study employs a VPeD model of a real-world installation of Styrofoam Insulation panels (See fig 32). The research sets-out to answer three questions:

1. what current theories, approaches and technologies support a virtual prototype modeling approach to pictographic instruction of assembly procedure
2. what features of an industrialized assembly environment support procedural task communication and how might pictographic instruction be tested for/within it
3. what conclusions can be drawn regarding the suggested approach's modality – the ability of a signal to manifest its message as an understood reality – and what suggestions might be made to strengthen a user-viewer's comprehension of it

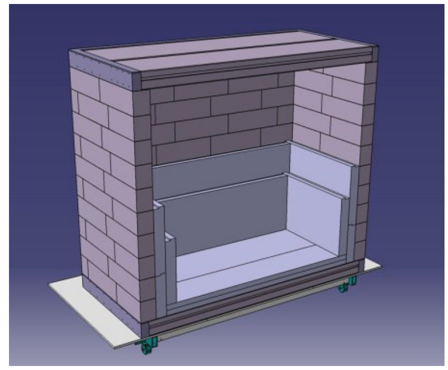

Fig. 31 Virtual Prototype of Short Lab

Fig. 32 Prefabricated Building Materials

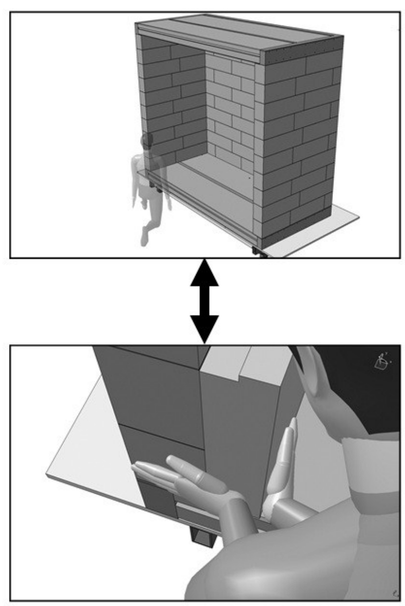

Fig. 33 VPiP Composite Pictograph

3.4 Background and Supporting Research

Virtual Prototyping (VP)

Virtual Prototyping (VP) is a recognized digital modeling technology with the capacity to represent 4D building information (Koo and Fischer, 2000; Dawood et al., 2003; de Vries and Harink, 2007). As a current AEC industry tool, VP is the practical realization of early speculative system-architectures (Darwiche et al., 1988; Fischer and Froese 1996; Eastman and Jeng, 1999; Harrison et al., 2001;

Eastman et al., 2011) and their analytic promise in application to construction's planning (Skolnick et al., 1990; McKinney, 1998; Riley, 1998). Modern VP programming takes into account the geometric constraints of 'real-world' assembly in a digital environment. VP's strength goes beyond time-scripted part animations and on-screen analyses such as clash detection (Hu and Zhang, 2011; Sampaio and Santos, 2011). As a modeling class, VP can contextually frame in-situ construction processes (Gou, 2009; Heng et al., 2011; Huang et al., 2007). To do so, a VP constructability programmer must consider real-world means and methods at a level of detail rarely addressed by construction specifications (Hsieh et al., 2006; Akinci et al., 2002; Waly and Thabet, 2003). VP programming requires one to specify digital geometric constraints for real constructability protocols. This programming regiment illuminates gaps in AEC production information (Gao et al., 2006; Kamat and Martinez, 2002) and the particularly shallow nature of graphic procedural representation in AEC production communications (Boukamp and Akinci, 2007; Johnston and Beliveau, 2010).

VP as Integrative BIM Technology

This research targets the realm of BIM technology and application development for integrated design management (Eastman et al., 2011). The VP application it proposes serves as a proof of concept for the "3D systemic innovation" argued for by Taylor (2007). VP's ability to programmatically consider both product design and construction processes is an interlinked lean-construction requirement (Brookfield et al., 2004; Halpin and Kueckmann, 2002). VP software - when a component of a digital process planning suite - is exactly the type of interface management solution suggested for integrating AEC project delivery (Jorgensen and Emmitt, 2009; Singh et al., 2011). VP's characterization of in-situ assembly practices is a powerful review tool encouraging project viability at the earliest stages of lean project development (Thyssen et al., 2008). The in-situ design-production communications VP supports sits squarely within the realm of ndBIM tools. ndBIM tools are intended to support multi-domain collaboration by highlighting user-context to the invested community (Aouad et al., 2005). Aziz (2012) suggests that VP modeling supports design's project integration. VP empowers client-viewers through managed communication of user-specific context (See Figure 33).

Lean Project Development / Industrialization

Factory-efficient, off-site, premanufactured, and lean are only a few of the terms associated with industrializing efforts in the Architectural, Engineering and Construction (AEC) industry (Ballard and Howell, 1998; Gibb, 2001). The oft-touted goals of systematized building production (efficiency, quantity, quality) are in themselves not new (Gann, 1996; Womack and Jones, 1996; Hopp and Spearman, 2000). While the productive benefits of industrialized construction are well documented (Blissmas et al., 2006; Tam et al., 2007; Eastman and Sacks, 2008) fewer negative consequences are ascribed to its application (Lu and Kamar, 2012). One persistent critique however, is industrialization's relationship to labor's production contribution (Taylor, 1911; Thomas and Sanvido, 2000). The tenants of that critique are suggestively split between the need to systematically represent labor's role (Watkins et al., 2009; McGrath-Champ and Rosewarne, 2009) and the still-untapped potential of IT applications in communicating onsite domain knowledge. (Jorgensen and Emmitt, 2008; Ballard, 2009; Alvanchi et al., 2012).

Construction research is deeply interested in the effects industrialization has on labor (McKone et al., 2001; Phua, 2004). Phua (2004) found that a key component to smooth transition between dynamic onsite assembly and controlled factory-like production was the contributing character of labor. Supporting researchers contend that the less than benchmark success in manufacturing's application to construction may be attributed to how labor comprehends construction work and organizes itself around required tasks (Watkins, 2009; Paez et al., 2005). Nawari (2012) attributes ineffectiveness in lean enterprise translation to the onsite construction practices of labor. The authors Lou and Kamar (2012) suggest that traditional project delivery packages are incongruent with 'component-based' design and production. Their critique recognizes an increased reliance on under-skilled labor delivering building systems with higher imbedded value. Toner and Coates (2000) add importance to a theme of uncharacterized assembly contributions by labor, suggesting that industrialized AEC production environment may actually deskill onsite workers. Green and May (2005) see industrialized production as lowering design detail, where McGrath-Champ and Rosewarne (2009) identify it as decreasing allowable assembly tolerances and time for completion.

Pictographic Instruction

The medium used in this research to communicate VPeD as procedural instruction to in-situ workers is the pictograph. Pictographs, unlike icons, "are not arbitrary graphic entities, but rather simplified pictorial representations of objects or actions which are comprehensible by familiarity or pragmatic intuition" (Bertoni, Stoffel and Weniger, 1991). VP capacity to program identifiable anthropomorphic imagery (e.g., hands and feet) through an ergonomic utility makes it a logical communicator of AEC production information. The static-graphic instructional representation of VP constructability programming as suggested by this author is supported by cognitive science research in sequential 2D assembly graphics (Agrawala et al., 2003). A graphical representation of assembly procedure is further supported by human cognitive traits inferring motion and physical force (Mayer, 2010; Toskos and Boroditsky, 2010). VP programming outputs are well suited to expressing still-graphic cues of directionality, temporality, and human form (Ellis et al., 1996; Krull and Sharp, 2006; Heiser and Tversky, 2005). VP programming can efficiently frame 'real-world' assembly protocols, minimizing visual clutter associated with cognitive overload (Paas et al., 2003). Tversky et al., (2002) suggested that still-graphic instructional cues are just as effective as animations in assembly communication. Watson et al., (2008) did identify assembly animations as producing faster 'first-build' times over still-frame graphics. Instructional assistance from augmented reality (Baird and Barfield, 1999; Woodward et al., 2007) and handheld technology (Izakara et al., 2007; Heesom and Mahdjoubi, 2004) – while applications VPiP could ultimately support - are not within in the current scope of this research. The direct attachment of pictographic assembly information to prefabricated building materials seems a more practical and immediate manufacturing assist (Heesom and Mahdjoubi, 2004; Holmquist et al., 2004; Jang and Skibniewski, 2008).

3.5 Systematized Construction Protocols

This work extends prior research into Virtual Prototype Optimization of Design (VPED) and its suggested compatibility to pictographic communication. That research utilized VP programming to communicate an enhanced design-engineering plan of a mobile building-envelope testing laboratory.

Key results from VPeD application to the Short Lab's (SL) production were:

- Real-world and digital assembly constraints translate geometrically when programming VP for constructability
- VPeD production information can be characterized for graphical representation to a User-Viewer Labor (UVL)
- VP Instructional Pictograph (VPiP) beta-testing suggested that VPeD can communicate graphically to in-situ labor

VPeD research examined an industrialized wall-assembly utilizing aerated-concrete blocks. To add validity to the earlier beta-test, this paper proposes that an alternate assembly composed of Styrofoam Board Insulation Panels should be tested (See Figure 34). It was theorized that a change in production materials would help identify the geometric, anthropomorphic, and procedural protocols contributing to its industrialized assembly.

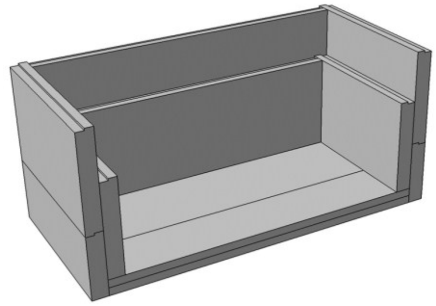

Fig. 34 VP of Insulation Sub-Assembly

Fig. 35 Labor-Part Interface

Fig. 36 VPiP Assembly Procedure

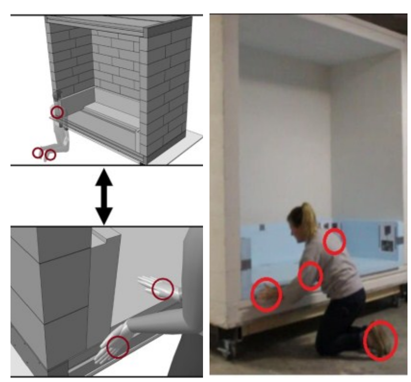

Fig. 37 VPiP Posture Profiling

This work begins by graphically characterizing the key protocols of an assembly procedure, such as a laborer's interface with a building material (See Figure 35). Furthermore, it frames protocols to maximize their relevance as visual assembly referents (See Figure 36). UVL appreciation of such referents is measurable through an accounting of their posture and position as they mimic provided imagery (See Figure 37).

This paper therefore proposes to define the minimal representative bandwidth facilitating pictographic assembly-task instruction. Its results are intend to support a communications theory that virtual prototyping can facilitate the graphical profiling of base-line modality relative an industrialized assembly task.

3.6 Short-Lab Test

Methodology

16 participants were assigned into four groups, each tasked to complete 13 panel installations. All building materials used during the trials were reset at the end of each test. Testing assessed three areas: 1) The posture and limb location of labor during final assembly, 2) The time to final assembly, 3) accuracy of final assembly. One worker was randomly selected from their group. Each group waited for selection within a sequestered area. The chosen worker selected one insulation panel from the top of a material pile in the assembly area. Laborers were unaware that the material pile had been pre-figured to facilitate a logical assembly sequence. The material pile ordering identified by VPeD was the same across all trials. Participants were told to use any and all assembly information made available to them to locate and place their panel into its most logical final assembly position. Workers were told they may encounter a part that was incorrectly assembled and that they should correct anomalous prior work to fit their assembly needs.

A distinction in assembly information was established between the testing groups. One group received no information about the assembly (NIT). Participants in this group were allowed to inspect the fully insulated Long Lab sitting directly adjacent to their testing station (See Figure 38). The insulated Long Lab was hidden to all other test groups. A second group received standard construction documentation illustrating proper panel placement (SIT). SIT participants received 2D plans, pertinent lab sections, and two alternative 3D perspectives of the lab as their assembly instruction (See Figures 39 and 40).

VPiP test participants were provided two distinctive pictographs attached to either-end of their panel (See Figure 33). An observer recorded all participants' hands, feet, and torso positions judged as achieving the postures indicated by on-board pictographs. Specificity in right and left hand/footedness was required for scoring. Completion time for all instruction trials was measured from the moment of material contact to the UVL's indication of final assembly. Final assembly accuracy was judged against the VPeD. The test monitor used a corresponding VPiP instruction set to record posture mimicry during the experiment. All procedures were video recorded for review and score corroboration.

3.7 Short-Lab Test Results

Posture Mimicry

Fig. 38 No Information Test (NIT)

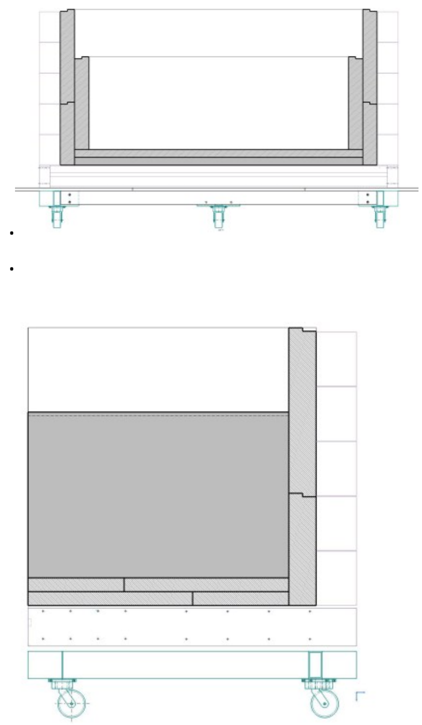

Fig. 39 SIT Production Details

Fig. 40 Standard Info Test (SIT)

Test results are charted within the Appendix of this paper. An iconographic summary of Group A and B's combined modality scoring is also presented therein. Test results showed an average torso posture score of .53 for group A and .46 for group B, on a scale of +2.0<>0.0 with zero representing no observable posture replication. Foot positioning provided a categorical average of .8 for Group A, and .73 for Group B, upon the same scale. Hand mimicry for group A scored 1.35 and 1.0 for group B.

9.6% of the 26 VPiP assemblies indicated participants achieving full mimicry of all five posture protocols. 55% of all observed postures exhibited both a torso protocol (a laborer's key referent for assembly location) and at least two other extremities in compliance. For this particular test case, a base-modality score of 2.5 is suggested as the minimum threshold score for successful pictographic assembly communication.

Time of Assembly

Regarding panel assembly times, VPiP Group A was excluded due to their participation in an extra assembly task (material cutting). VPiP Group B's total time taken to assemble all 13 panels was three minutes and fifty-one seconds (-3:51) less than SIT times-to-completion. VPiP Group B's totaled time for all panel assemblies was six minutes and twenty-seven seconds less (-6:27) than the NIT times-to-completion. VPiP's assembly-time savings averaged across all panel types was twenty-seven seconds (-:27sec) per panel. VPiP's time to total assembly of the 13 panels was 49% quicker than traditional graphic construction communication and 191% faster than the no-instruction scenario.

Assembly Error

The assembly error ratio between VPiP, SIT, and NIT was significantly lower for pictographic communication when considering anomalous placement across each trial's 13 panels: 0.07: 0.23: 0.38 percent respectively. The ratio of average time spent by a worker placing incorrect assemblies under VPiP, SIT, and NIT was: 22 seconds, 135 seconds, and 117 seconds respectively. VPiP mean-time allocated to anomalous assembly was 500% less than SIT, and 430% less than NIT performances. (Note, error-time calculations did not include time spent in downstream scenarios fixing encountered mistakes to facilitate proper assembly).

3.8 Data Observations

While this study acknowledges the necessity for larger sampling in future research its modest findings support the beta-test suggestion that VPiP is an effective signaler of in-situ assembly procedure. Validation of the beta-test's premise can be found in the shorter time for assembly and its lower number of assembly errors.

Fig. 41 Error Propagation (NIT)

One error type VPiP minimized was the associative error(s) shown in Figure 41. That figure illustrates three sequential errors made by UVL's during the NIT assembly trial. Each UVL assembled their part based upon an incorrect assessment that observed in-situ parts were correctly assembled. Uninstructed labor's acceptance of prior errors promoted further anomalies and pushed the lab farther away from correct assembly. A careful examination of the real-world prototype made available to labor would have indicated their compounding errors.

Fig. 42 Error Propagation (SIT)

A second type of observed error was one propagated specifically by part geometry. In this case, vertical panels had a direction-specific 'tongue and groove' connection. Figure 42 shows a UVL reviewing provided construction information to verify and guide panel assembly. The scenario that worker encountered had a previously installed panel placed 180 degrees incorrectly. In this case the anomalous part provided the base for the active part. The UVL's panel would fit; however, without error identification

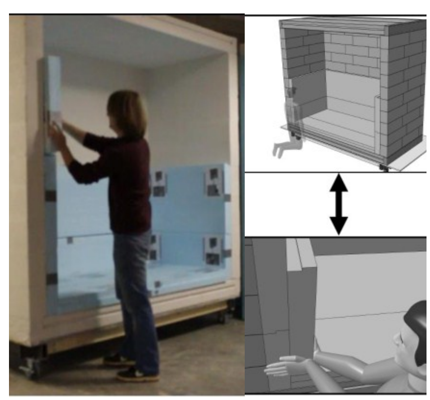

Fig. 43 Single Instance of VPiP Error

and re-work the active part would assemble improperly. In this case, an arguably weaker instructional signal sent by standard production information failed to cue the UVL's attention to both the prior error and correct assembly. The final result was second assembly error.

Both NIT and SIT error cases illustrate in-situ assembly conditions that proved stronger than the instructive modality expressed by the construction information.

Figure 43 illustrates the sole assembly error in the VPIP trials. The figure shows a worker influenced by factors contributing to SIT and NIT modal failure. First, the UVL encounters no referent part that can definitively cue proper assembly of the active part. Secondly the active part had multiple edge conditions that increased assembly options and the odds of mating the panel incorrectly. Thirdly the scenario's VPiP imagery did not, in this particular case, convey desired assembly protocols strongly enough to guide proper panel installation. It is suggested here that, had the UVL mimicked the foot posture indicated by the VPIP work-location window, the odds of correct floor-level panel assembly would have been increased by ergonomic realty.

Setting supposition aside, what makes the sole VPiP error interesting is the correct placement of the following panel within the assembly sequence (See Figure 44). In this case, the UVL properly assembled their panel, ignoring the previous panel which had been installed in the wrong location. Visual inspection would have indicated the identical geometry of both panels and suggested a possible symmetry in assembly, yet the UVL correctly placed the active panel and disregarded the in-situ error. The on-board pictographic imagery for both panels was comparable, yet the modality of onboard pictographs in the subsequent assembly was obviously higher. In fact, that laborer scored a perfect 4.5 on the test's modality scale for primary placement. The previous assembly error, in comparison, exhibited a 2.5 modality score in primary placement. Neither case recorded a measurable modality score in the observance of secondary on-board VPiP.

3.9 Conclusions

This research provides information supporting the theory that non-verbal assembly cues derived from VP enhanced design can instruct labor toward a prefigure goal in a construction environment. Its findings suggest that when VP instructive pictographs are composed from VPeD programming, their characterization helps a UVL minimize assembly contribution of in-situ error which compounds and ultimately degrades enterprise investment in industrialized production. VPiP use of pictographic communication to boost assembly comprehension is in-line with other pictographic instruction research (Szlichcinski, 1984; Agrawala, 2003; Fischer and Schwan, 2010). However, a majority of this prior research has focused on visual signaling for much smaller assemblies. (Agrawala et al., 2003; Heiser and Tversky, 2005; Martin, 2007; Watson et al., 2008; Lau et al., 2011). As such, the results of this research stand distinct in regards to approach and application on a full-scale building product.

Error and Time to Assembly

Regarding VPiP time to assembly, trial observation showed VPIP decreased time-to-assembly verses traditional and non-instructional scenarios in all but three cases. Of note, VPiP tasks exhibited the least time spent on investigation of in-situ assembly information. This fact suggests

FIG. 44 VPiP Overrides Prior Error

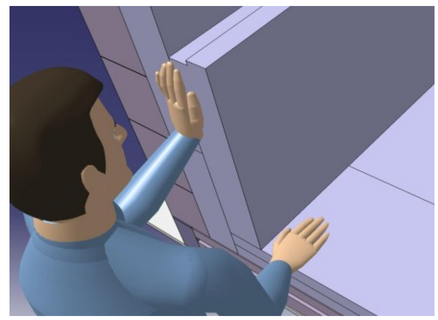

Fig. 45 VPiP Possible Cue Refinement

Fig. 46 Center Carry Resists Posture

Fig. 47 Mimicry of Both Onboard VPiP

that time expenditures in traditional and lower-informational assembly environments hold no guarantee of identifying embedded error or delivering proper assembly. The Time-Under-Error chart included within the Appendix of this manuscript illustrates how industrialized assembly under VPiP direction boosts resource-value by eliminating time and energy expenditures spent on error identification and resolution.

Instructional Modality

Regarding VPiP's capability to graphically signal procedure, modality testing showed hand mimicry exhibiting the highest modality score of all measured protocols. Positive hand-scoring should not be surprising as one of two pictographic windows represented the UVL engaging the building material. Furthermore, cognitive researchers advocate the instructional benefit derived from user-viewer visualization of hand gestures (Ellis et al., 1996; Fischer and Schwan, 2010). Nonetheless, testing criteria for hand mimicry was relatively strict: correct handedness, simultaneous posture engagement and its relative material positioning were all considered. Relatively few (11%) of the first-task pictographs scored a zero – meaning, most VPiP guided building-materials went into assembly under an appendage posture indicated by pictograph. The lower-torso (foot positioning) protocol communicated most poorly, scoring a zero in 36% (9/26) of instances where the UVL utilized the primary on-board pictograph. The low foot mimicry score can be compared to the 11% (3/26) zero-score in hand mimicry for primary pictographs:

Signal Weakness and Graphical Consideration

Figure 45 reconsiders the visual cueing factors contributing to the single instance of observed VPiP assembly error. Its anthropomorphic (hand) imagery has been reconfigured to impart more suggestive assembly cues. Its torso cueing was resynchronized to match the UVL-avatar position indicated by the work-location window (See figure 33). These suggested visual tweaks exemplify an iterative approach for boosting a UVL's assembly compliance through clear reinforcing visual cueing.

It is recognized that VPiP guided successful assembly despite low foot protocol scoring. Additionally, the single instance of VPiP error produced a zero foot score. This fact calls into question the efficacy of low-torso (foot) signaling as designed by this research. A new study should be conducted to better establish foot position relevance in assembly task communication. It is speculated that an independent pictographic window highlighting foot protocols would be necessary when instructing heavy-lift assemblies or operational environments where foot placement is constrained (e.g., on scaffolding).

Programmer In-situ Production Awareness

Finally, this study calls the VPiP programmer to task in relation to torso communication, as its mimicry missed on approximately 50% of all pictographs. The presence of low torso scoring illustrates that labor chose to deliver materials along a path of its own choosing – even when provided with anthropomorphic imagery indicating sound ergonomic assembly with part delivery. While this study looked to establish pictographic communication of assembly, the VPiP programmer must remain cognizant of real-world production factors (e.g., obstacles, debris, unnecessary expenditures of personal energy) that will sway human behavior over instructional modality. The low instance of secondary on-board pictograph mimicry is similarly critiqued. Due this tests small sample size, it is speculated that VPiP Group B missed more secondary protocols because their panels were delivered into assembly from a center-carry position (See Figure 46). In theory a center-carry position encouraged by pre-cut materials led to assembly protocols not characterized by the VPiP programmer. This suggested lack of in-situ detail within the VPiP may have overcome any intended graphical cueing. This notion is loosely supported by VPiP Group A’s higher secondary pictographic compliance score. Greater mimicry possibly encouraged by a desire to the check fittedness of their material manipulation (Figure 47).

Future Work

This research has shown that existing virtual prototyping technology, industrialized construction, and graphic-language theory, can be combined into an instructional format with communications merit. How pictographic imagery might be composed more effectively to boost its instructive modality is the fruit for future work. Further research might refine the cognitive range of assembly-task pictographs. Or, VPiP could be tested against a prefigured assembled error. Speculatively, VPeD modeling could prefigure all possible geometric errors for a bound assembly. Such information would theoretically form a geometric data-base tied to Augmented Reality (AR) inspection technology. In such an environment, when the in-situ laborer recognized an assembly error the system would provide prepared VPiP information communicating the optimal corrective action.

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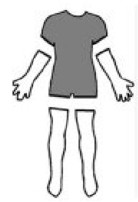
3.11. Appendix

3.11. A: VPiP Modality Summary (Part-A)

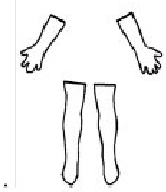


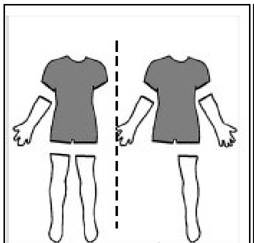
Modality: 4.5
Protocols Met: 2 (Feet) +2(Hands) + Positioning (torso)
Profile Occurrence: 5/52 **(10%)**
Primary |Secondary Ratio: 5|- - -
Percent of All Primary |Secondary Procedures: .19|- - -

Note:

Modality: 4
Protocols Met: (2+2)
Profile Occurrence Total: 1/52 **(2%)**
Primary |Secondary Ratio: - - - | 1
Percent of All Primary |Secondary Procedures: - - -|.04

Note:



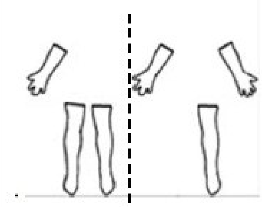


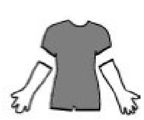
Modality: 3.5
Protocols Met: (2+1) + Positioning
Profile Occurrence Total: 7/52 (13%)
Primary/Secondary Ratio: 5 | 2
Percent of All Primary/Secondary Procedures: .19|.08

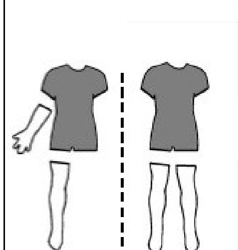
Note: Dual Hands Condition 5/7 (71%)

Modality: 3
Protocols Met: (2+1)
Profile Occurrence Total: 3/52 **(5.7%)**
Primary/Secondary Ratio: - - - | 3
Percent of All Primary/Secondary Procedures: - - - |. 11

Note: Dual Hands Condition: 2/3 (66%)







Modality 2.5
Protocols Met: (2)+ Positioning
Profile Occurrence Total: 13/52 **(25%)**
Primary/Secondary Ratio: 10|3
Percent of All Primary/Secondary Procedures: .38|.11

Note:

Dual-Hand occurrence: 8/13 (62%).

Hand-Foot occurrence: 5/13 (38%).

Dual Foot occurrence: - - -

3.11. B: VPiP Modality Summary (Part-B)

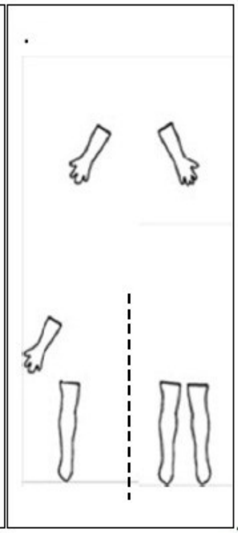
Modality 2
Protocols Met: (2)
Profile Occurrence Total: 8/52 **(15%)**
Primary/Secondary Ratio: 2|6
Percent of All Primary/Secondary Procedures: .08|.23

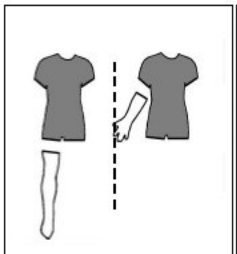
Note:

Dual-Hand occurrence: 3/8 (.37%)

Hand-Foot occurrence: 2/8 (25%)

Dual Foot occurrence: 3/8 (.37%)



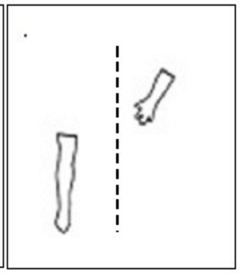


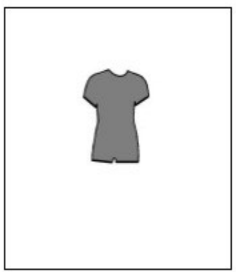
Modality 1.5
Protocols Met: (1)
Profile Occurrence Total: 1/52 **(1.9%)**
Primary/Secondary Ratio: 1|- - -
Percent of All Primary/Secondary Procedures: .03|- - -

Note: Single Foot-Hand Ratio (0:1)

Modality 1
Protocols Met: (1)
Profile Occurrence Total: 4/52 **(7.7%)**
Primary/Secondary Ratio: 2|2
Percent of All Primary/Secondary Procedures: .08|.08

Note: Single Foot-Hand Ratio (2:2)

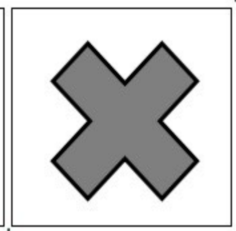




Modality .5
Protocols Met: (0) +Positioning
Profile Occurrence Total: 0/52 **(0%)**

Note:

Modality 0.0
Protocols Met: (0)
Profile Occurrence Total: 10/52 **(19%)**
Primary/Secondary Ratio: 0|10
Percent of All Primary / Secondary Procedure: ---|.38



3.11. C: Protocol Profiling Data (Group A)

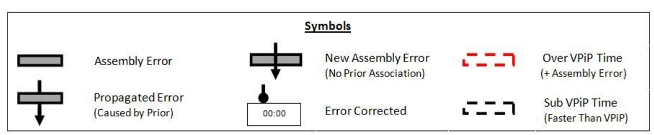
Pictograph ID.	User ID.	Foot Position ID *Both exact +2; One correct +1; both wrong 0.*	Hand Position ID *Both exact +2; One correct +1; both wrong 0*	Worker Position (Torso) ID *Achieved : **T*** *Not Achieved: **X***		Score Total	(+T) With Torso		(-X) Torso Miss		
1L	A	2	2	T		4	4				
1R		1	0	X		1			1		
2R	A	1	0	X		1			1		
2L		0	2	T		2	2				
3R	A	0	1	X		1			1		
3L		2	0	X		2			2		
4L	C	1	1	T		2	2				
4R		0	0	x		0					
5L	D	1	2	T		3	3				
5R		1	1	x		2			2		
6R	D	2	2	T		4	4				
6L		1	2	X		3			3		
7L	B	1	1	T		2	2				
7R		1	2	T		3	3				
8L	D	0	2	T		2	2				
8R		1	1	x		2			2		
9R	A	0	2	T		2	2				
9L		0	2	T		2	2				
10L	C	1	1	T		2	2				
10R		1	2	X		3			3		
11R	D	1	2	T		3	3				
11L		0	1	X		1			1		
12R	C	1	1	T		2	2				
12L		2	1	T		3	3				
13L	C	0	2	X		2			2		
13R		0	2	X		2			2		
						AVE	***(T) av***	***%***	**(X)av**		
All 26 protocols		All #'s Mode = 1		(T) M=1; (X) M=0		1.07	1.28	**+19.6%**	**1.8**	**+68%**	
1st proto(s) only		1st proto Modes = 1		(T) M= 1; (X) M=01		1.15	1.3	**+ 13%**	1.3	**+13%**	
						+ 7.5%	**+1.5%**	% Chg	**- 27%**	% Chg	
Catgr. Score Ave		.8 (mode=1)	1.35 (mode =2)	.53(T)					.46(X)		
1st proto only ave		.85 (mode=1)	1.46 (mode=2)	.77(T)					.23(X)		
% Change		**+ 6.25 %**	**+ 8.14 %**	**+ 45%**					**- 50%**		

3.11. D: Protocol Profiling Data (Group B)

Pictograph ID.	User ID.	Foot Position ID *Both exact +2; One correct +1; both wrong 0.*	Hand Position ID *Both exact +2; One correct +1; both wrong 0*	Worker Position (Torso) ID *Achieved : **T** Not Achieved: **X***		Score Total	With Torso (+T)		Torso Miss (-X)		
1L	R	1	2	T		3	3				
1R		0	0	X		0			0		
2R	R	1	2	T		3	3				
2L		0	0	X		0			0		
3L	W	2	0	X		2			2		
3R		2	0	x		2			2		
4L	Y	0	1	T		1	1				
4R		0	2	x		2			2		
5L	Y	2	2	T		4	4	**ALL**			
5R		2	1	x		3			3		
6L	G	1	1	T		2	2				
6R		0	0	x		0			0		
7L	R	0	2	T		2	2				
7R		0	2	T		2	2				
8L	W	0	2	T		2	2				
8R		0	0	x		0			0		
9R	Y	2	2	T		4	4	**ALL**			
9L		0	0	x		0			0		
10L	G	2	1	T		3	3				
10R		2	2	x		4			4		
11L	G	0	2	T		2	2	***Error***			
11R		0	0	X		0			0		
12R	Y	2	2	T		4	4	**ALL**			
12L		0	0	x		0			0		
13R	Y	0	0	x		0			0		
13L		0	0	x		0			0		
						AVE	***(T) av***	***%***	**(X)av**		
All 26 protocols		All #'s Mode = 0		Mode = (X)		1.73	2.6	**+50%**	.9	**-47.9%**	
1st proto(s) only		1st proto Modes = 2		Mode = (T)		2.46	2.7	**+ 9.7%**	1	**-59%**	
% Change						**+ 42%**	**+3.8%**	% Chg	**+11%**	% Chg	
Catgr. Score Ave		.73 (mode=0)	1 (mode =0,2)	.46(T)							
1st proto only ave		1.0 (mode=0,2)	1.46 (mode=2)	.84(T)							
% Change		**+37 %**	**+ 46 %**	**+ 82%**							

3.11. E: Time Under Assembly Error (Group B)

Panel		VPIP (Group B)	Standard Info.	No Info.	VPiP (Time to Asm)	SIT (Compr VPiP) +/-	NIT (Comp VPiP) +/-	
1	M:S	:22	:25	1:15	:22	+:03	+ :53	
2		:19	:40	:20	:19	+.21	+:01	
3		:41	**1:00**	1:02	:41	+.19 error	+:21	
			error					
4		:40	1:27	**:32**	:40	+.47	+:08 error	
				error				
5		:49	:46	**1:04**	:49	**-.03**	+:15 error	
				error				
6		:53	1:45	**1:48**	:53	+:52	+:55 error	
				error				
7		:43	:23	**:50**	:43	+:20	+:07 error	
				error				
8		:31	:28	:51	:31	+:03	+:20	
9		:19	:15	**:55**	:19	**-:04**	+:36	
10		1:42	**3:31**	3:54	1:42	+1:49 error	+2:12	
			error					
11		**:22**	:21	**:39**	:22 error	+:19	+:17 error	
		error		error				
12		:16	:14	**:37**	:16	**-:02**	+:21 error	
				error				
13		:32	**:45**	**:49**	:32	+:07 error	+:17 error	
			error	error				
					(1)	(3)	(7)	Error total
					.48	9:55	11:17	TTime under E
Total Asm. Time		8:09	12:00	14:36				
Ave. Time / Panel		:37	:55	1:07	.48	3:18	1:36	TTot Under E / ETot



4. CONCLUSION AND FUTURE RESEARCH

4.1 Summary of Works

Paper one illustrates that the geometric assembly constraint programming required by virtual prototyping, is an effective constructability review when applied to AEC building information. This research also shows how the software interface used to program a virtual constructability review can be pictographically scripted into an instructive communications format – one capable of cueing workers along an optimized assembly sequence. The application of VP enhanced design to instructive communications is an idea supported by existing cognitive science research. The suitability of that application is strengthened by findings which suggest pictographic communication as a method for cueing human comprehension of the assembly work task. Further details on the programming and initial translation of VP programming into a graphic language can be reviewed in paper one of this manuscript.

Paper two provides information supporting a theory that non-verbal assembly cues derived from VP enhanced design can instruct labor toward a prefigure goal in a construction environment. Its findings suggest that when VP instructive pictographs are composed from VPeD programming, their characterization helps a user viewer laborer (UVL) minimize assembly contribution of in-situ error which compounds and ultimately degrades enterprise investment in industrialized production. The studies observational trials showed VPIP decreased time-to-assembly verses traditional and non-instructional scenarios. Of note was VPiP guided labor spent the least amount of time on in-situ investigation of assembly information; a resource expenditure which held no comparative guarantee of identifying embedded error or delivering proper assembly. Further detail on the testing and results of virtual prototype instructive pictographs can be reviewed in paper two of this manuscript.

4.2 Conclusions

The evidence gathered from both papers directly answers the research questions posed in the introductory chapter of this manuscript. Both the beta-test of VPeD and VPiP assembly procedure showed measurable modal efficacy. This fact was first observed in novice UVL's overcoming cognitive bias acquired from their construction of a similar assembly. The second confirmation comes in the form of a correct industrialized sub-assembly, delivered by novice labor under no instruction other than VPiP.

Geometric constraint-based programming is recognized by this research as the primary interface of virtual prototype constructability modeling. Both papers provide example where VPeD/iP assists direct constructability translation. The first case successfully integrated block assembly practices observed to be naturally desirable by unguided labor, with the specificity of a VP design constructability check. The second example showed that a pre-figured assembly pictographically characterized from its virtual prototyping communicated more effectively compared to standard AEC production information or a real-world prototype.

A UVL's interaction with the proposed VPeD/iP system is done so through the lens of their cognitive and experiential biases. The structured approach of this research has shown that pictographic assembly instruction derived from VP constructability programming is modal - despite the internal programming of the human laborer. How VPeD/iP may be framed to boost signal resonance with human work-domain tendencies and synchronize with industrialized expectation is a foundational question for future research.

4.3 Future Work

Specific recommendations for future work can be found at the conclusion of both papers supporting this manuscript; however, some closing thoughts on the proposed VPeD/iP approach and its feasible application follows.

The graphical data supporting VPeD/iP is a logical fit to augmented reality (AR) technologies designed for construction environment application. AR support of project communications is a popular research topic. For example, (Heesom and Mahdjoubi; Izakara) both proposed AR graphical cueing of points-of-interest in a building project. The authors (Baird and Barfield; woodward) both proposed handheld AR technologies integrating graphical views of a construction site. Of particular interest is research

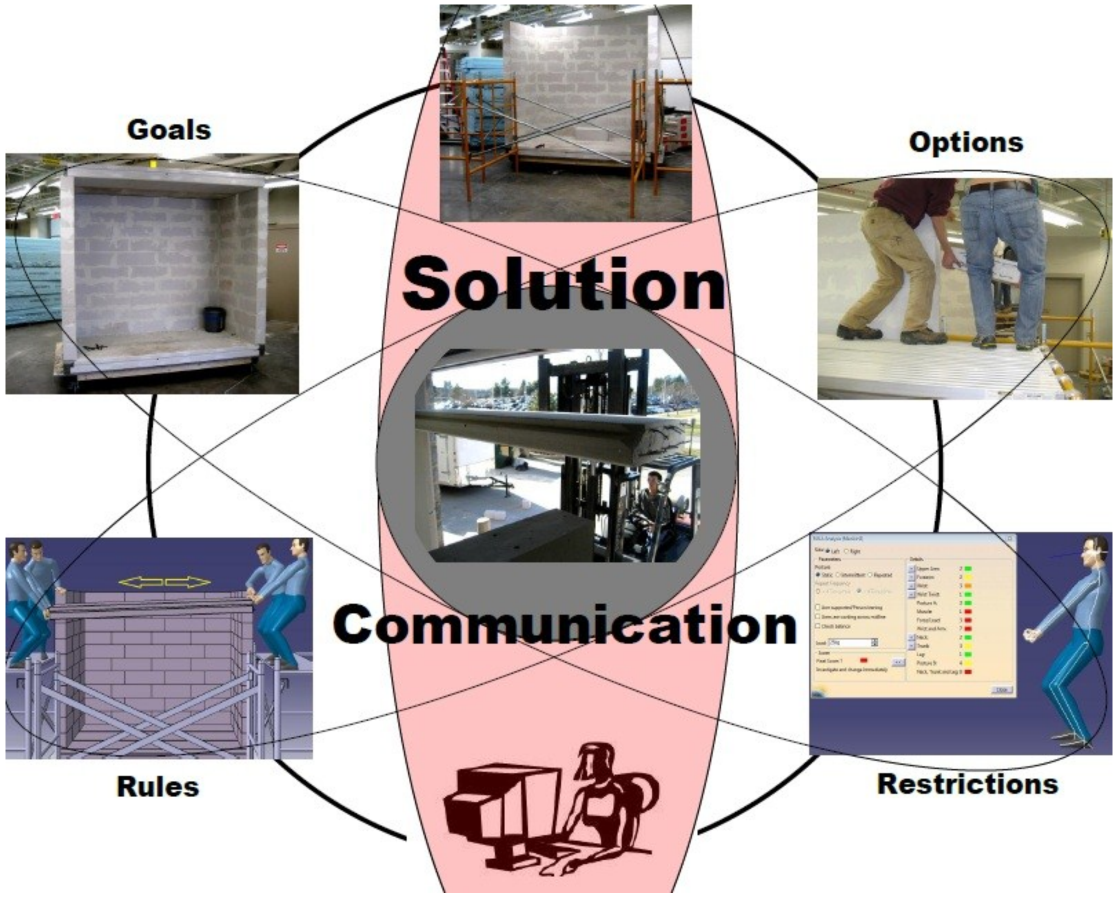


Fig. 48 VPeD/iP Re-characterized as an AEC Solutions Communicator

placing Quick Response (QR) bar codes on mechanical parts to induce AR detailing of maintenance procedures and control tasks (Wang and Dunston). It is easily foreseeable that VPeD/iP assembly communications could be fed in-situ to AR users by QR application to individual building materials. Realistically, QR application could be controlled in-factory by BIM-driven material procurement tied directly to the VP model. Integrated ID applications are be in-line with current research attempting to track onsite building materials (Holmquist et al.; Jang and Skibniewski).

This researcher also identifies parallel testing environments suitable for development of optimized pictographic instruction of construction. There are current example of detailed ergonomic analysis of industrialized construction procedure (Nussbaum et al.). Other research provides digital humanoid assessment of industrialized worker motions with an optical capture system (Du and Duffy). Research into real-time capture of insitu construction posturing is also being undertaken (Ray and Teizer). This author speculates that real-time procedure capture integrated with the VPeD/iP approach would increase pictograph specificity. For example, zones of acceptable posture achievement could be pre-identified and digitally recorded during a test of VPiP; thereby, directly linking future pictographic image alteration to the refinement of modality.

It is also conceivable that the prefigured geometric specificity of VPeD could be combined with a real-time motion capture system – for training purposes. The suggested combination would not only measure instructional efficacy but provide an effective metric for gauging a worker's tectonic competency. This theory can be observed in the results of Table (3.11.E) within paper two's Appendix. There it can be seen that panel nine's NIT worker took less time than panel ten's SIT worker to find and correct two imbedded assembly errors. The production savings may suggest a worker's level of skill. Interestingly, panel tens' SIT worker had traditional assembly information at his/her disposal, yet succumbed to an embedded error. In this case, the time spent to ultimately propagate error may speak to a laborer's current field-training or aptitude.

The above research should make the value of VPeD/iP development abundantly clear. Virtual prototyping utilized as a ndBIM approach to data sharing and AEC domain integration can empower designers, engineers and construction programmers to foresee project solutions before they are problems and effectively communicate optimal choices real-time to invested project participants.

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6. APPENDIX

6.1 Supporting Papers Also By This Author

6.1. A: *Using Virtual Prototyping to Evaluate Panelized Construction*

USING VIRTUAL PROTOTYPING TO EVALUATE PANELIZED CONSTRUCTION

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ABSTRACT

US residential homebuilders are currently attempting to increase production by applying manufacturing techniques to areas of their construction process. One increasingly popular construction technique is the utilization of panelized wall systems. The US Department of Housing and Urban Development studies Industrializing the Residential Construction Site identified numerous production interrelations regarding panelized construction in the areas of: product delivery, crew and panel sizing, panel preparation and staging, panel to slab, panel to panel, and panel to mechanical system integration (O'Brien et al, 2000; 2002)(Wakefield et al, 1999; 2001). This paper examines the potential utility of prototyping site-gathered panel assembly information for further examination of these integrative production issues.

This paper presents the production methods of panelized construction, using prototyped components modeled within a virtual site environment. Assembly scenarios are Prototyped to highlight assembly information requirements for panelized construction, with current production scenarios used to examine known production efficiencies. Finally, the utility in virtual prototyping this application is assessed.

Keywords: Assembly Information, Panelized Residential Construction, Virtual Prototyping

INTRODUCTION

This paper demonstrates the applicative capacity of present virtual prototyping methods to qualitatively assess onsite construction activities. Three areas developed within this paper to explore this capacity are:

- The application of relevant construction information to a virtual process model.
- The demonstration of virtual prototyping technology's capacity for modeling a panelized construction process.
- A discussion on present virtual prototyping technology's ability to adequately interface with, test and inform a panelized work environment.

This research addresses each of these virtual prototyping concerns through visualization of the onsite production process for wall panelization. In applying virtual prototyping to

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this type of production process, we show how a technology can expose the relevant informational and physical parameters that inform an efficient production process.

The study begins with the collection of relevant site-specific factors, product data and relevant ergonomic factors. Three-dimensional product models are defined in relation to collected site data. Each model is then sequentially defined by observed site processes associated with panelized construction. This paper's development of a prototyped process framework includes:

- Definition and virtual modeling of the panelization processes in three alternative Macro assembly analyses.
- Definition and virtual modeling of constituent Micro assembly procedures, for example, those activities related to panel connected with shipment and unpacking, staging and layout, manipulation and assembly.
- Virtual identification of known production inefficiencies and suggestions of applicable analysis tools presently available for virtually analysis of these.

Illustrations of both Macro and Micro level virtual prototyping studies are provided in the paper. In closing the paper will suggest quantitative assessment applications for potential analysis of actual production efficiency and efficacy.

Virtual Prototyping

The architectural, engineering and construction industry's interest in virtual modeling is developing with a growing body of research related to abstract and discrete modeling. Simulation has been widely applied by academia to construction. Construction visualization efforts include Petri nets (Wakefield, 1999) and modeling frameworks such as CYCLONE (Halpin, 1977), RESQUE (Chang, 1986), GPSS (Scriber 1989), COOPS (Liu, 1991), DISCO (Huang and Halpin, 1994), and STROBOSCOPE (Martinez 1999). Researchers have also focused on visualization to examine construction process (Fischer and Kam, 2002). With industry pervasive Web-based interconnectivity and standardized CAD-type project platforms an attempt is being made in construction to achieve those production benefits realized in the manufacturing engineering and materials management disciplines. Their industrialization successes, built on visualization methodologies and concurrent-engineering principles, is typically envisioned for construction as a transparent project communication framework linking client requirements, design, engineering, and supplier databases, to contractor and facility management implementations. (Kamara and Anumba, 2000; Jeng and Eastman, 1999; Anumba and Evbuomwan , 1997). An example of such efforts can be found in Industry Foundation Classes (IFC) that are, at present, attempting to provide an ubiquitous communication framework from divergent forms of information building simulation software that automatically acquires building geometry and other building data from project models created on compliant CAD type softwares (Fischer and Kam, 2002; Bazjanac and Crawely, 1997).

While this paper does not intend to investigate application interconnectivity for construction process modeling, such as the IFC frameworks, it does intend to highlight

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present parametric requirements for applying virtual prototyping to known construction sequences. These requirements are directly linked to the present abilities of desktop CAD and process-modeling software packages along with accurate information derived from building product manufacturer's design specifications and site-specific construction information. This paper will show that with this combination of information and technology the following is possible:

- The creation of CAD based objects file
- The translation of CAD based files into desktop virtual prototyping software.
- The ability to produce object oriented three-dimensional models.
- Programmable sequencing of object and object path projections.
- Prototyped interference checking for assembly.
- Virtual humanoid ergonomic manipulation and object interaction.
- Accurate object model parameters with a virtual physics package representing weight, joint and hinge interactions, rotational and translation speeds.
- Theoretical analysis of manufacturing timelines, worker calorie expenditures, and National Institute of Occupational Safety and Health (NIOSH) worker lifting standards.

Homebuilding Panelization Factors

The Department of Housing and Urban Development is encouraging the use of alternate manufacturing-based homebuilding technologies to evaluate, demonstrate, and advance the current state of the art of housing in the areas of Durability, Energy Efficiency, Environmental Impacts, Safety, and Affordability. As previously stated, this paper's research focus is on the virtual prototyping examination of one of these technologies, namely the use of panelized wall systems for construction.

In 2002 US homebuilders broke all previous records with new-home sales totaling close to a million units. Despite record production, relatively few of the houses utilized panelized wall systems to speed production. Most recent figures suggest only 5.2 % of the linear feet of light frame walls in residential construction utilized panelized construction; however for high-volume production homebuilders, the use of manufactured wall panels is one preferred strategy for increasing production efficiency (HUD, 2002).

As a production shift away from traditional "stick-built" framing, panelized systems fit well with larger volume enterprises that offer relatively standardized site-built single and multifamily home models. Their choice of panelized system is a response to concerns related to higher raw material costs, increased reliance on inexperienced labor, and quality production. A recent HUD report prepared by the National Association of Home Builders (NAHB) Research center concludes that, "on site wall construction using panelized wall systems is simplified and accelerated for reduced labor and time demand in the structural installation stage". A major corporate homebuilder using panelized wall systems estimates that panelization has resulted in cost and time savings, with factory-built parts savings nearing about $3,000 to $4,000 per house and slashing 10 days off the average 110-day construction process.

6.1. A: *Using Virtual Prototyping to Evaluate Panelized Construction*

THE PANELIZED CONSTRUCTION PROCESS

Wall panels

The panelized wall systems considered for this study are typically factory framed using 2x4 dimensional lumber, they are un-insulated interior and exterior load bearing panels with pre-attached external sided wall sheathing (typically OSB). Panel sizes can vary from 2-12 feet in length and 8-9 feet in height. Panel framing components included top and bottom plates, cripple studs under and above openings, windowsill plates and headers, exterior sheathing, along with any supplemental bracing or connection hardware.

Wall panel design is typically based on architectural plans submitted to the panel manufacturer by the homebuilders' architectural or engineering departments. The panel manufacture decides on how best to subdivide a wall into individual panel sections before production. Panel manufactures provide a wall panel assembly plan to guide onsite production, which identifies each wall panel in its appropriate on-site position. This assembly plan typically shows the foundation outline and an inventoried listing of each panel with its corresponding dimensional characteristics. Each wall panel's assembly position is identified by a corresponding reference number, which is affixed to the panel at the factory.

Panels are typically palletized for shipping efficiency. Shipping weight and pallet dimensionality are primary considerations in onsite delivery. Interior and exterior panels typically arrive separated by pallet. Normally wall panel stacking order within the shipping pallet is neither numerical nor sequential (relative to actual wall layout). The number of panels per pallet depends largely on shipping constraints. The weight and size of the panels depends on the selected wall sheathing and fenestration options, and foundation floor plan characteristics.

Pre-assembly

Palletized panels usually arrive onsite close to the completion of the foundation. Wall foundations are usually reinforced concrete slab-on-grade or plywood and wood framed floor systems over basement walls. A line layout is typically begun along the longest unbroken exterior slab face before framing begins. A framing Forman will chalk and square dimensional exterior and interior wall placement lines onto the framing pad, directed either by architectural wall plans or manufacturer-supplied wall layout plan (according to availability.) Corresponding panel identification numbers were typically not indicated on the slab at this time. Any in-slab mechanical system penetrations can be crosschecked for potential wall panel interferences at this time.

Field Assembly

Two to four workers typically lift panels from the delivery pallet. A layout Forman is typically present to help direct and place panels into their corresponding positions. Workers identify and transition panels to the location identified by the chalked layout and wall panel assembly plan. Once in position, a thin polystyrene weather seal is typically added to each panel along the panel's base plate. If foundation anchoring is necessary for the panel it is drilled at this point. The panel is then ready to be stood on its correct foundation/deck position. The panel's placement is then checked for and squared in relation to the layout line and any adjacent wall panels. Once flush, the panel is fastened to the foundation/deck with standard fastening materials. Panel-to-panel connections are accomplished at this point. Wall panel to the floor deck stabilization is then achieved with standard 2x4 lumber. Bracing is used only as temporary stabilizing technique, with perpendicular panel-to-deck squaring not set until all adjacent wall panels have been attached into one unified and coplanar wall unit. Smaller panels affixed to previously set and stabilized panels rarely receive bracing. Larger dimension panels and unsheathed interior wall panels typically receive bracing. Works then return to the delivery pallet and retrieve the next selected wall panel.

THE VIRTUAL CONSTRUCTION PROCESS

The virtual assembly sequences created for analysis reflect observed onsite work process. Many factors contribute to differences in assembly procedure and sequencing such as: availability and clarity of layout information, crew size and experience, slab characteristics related to the number of corner conditions, cumulative lengths of exterior wall, panel sizing, and worker preference to adjacent-panel or an alphanumeric-adherence.

For the purpose of analysis the on-site panel assembly was broken into Macro and Micro assembly processes. Both processes are separated into three distinct virtual work sequences, with sequencing derived from the understanding of actual onsite assembly processes. The Macro assembly process is comprised of three different material path sequences for wall panel assembly. The Micro assembly process is also comprised of three subsequences; each containing linked work activities associated with a specific assembly period for one wall panel. This separation is intended to provide the framework for future quantitative analyses in efficiency and efficacy of panel wall assembly.

The virtual modeling process also requires an electronic representation of materials used for assembly. The sequence of steps for the input of this information is as follows:

1. Dimensionally accurate panels and foundation/slabs are reproduced three dimensionally using the panel manufacture's supplied product data.
2. Each panel is created as an un-rendered poly-line construction and then saved as an individual AutoCAD file.
3. Once translated, an AutoCAD file is imported and saved as an individual object file on the virtual prototyping platform.

The virtual prototyping software used for this research allows for each wall panel to be manipulated into a stacked pallet configuration representative of the pallet configurations found on site. Once the virtual panel pallets are organized and incorporated with the slab model the virtual scene is saved and ready for simulation.

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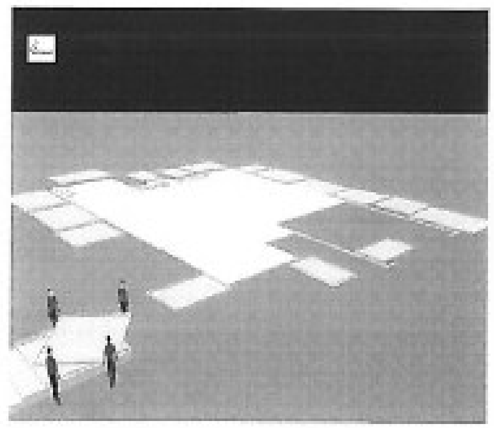
The simulated attachment of work paths to a material (wall panel) is the final stage of modeling before analysis begins. The employed prototyping software allows for object oriented programming of linear sequences (positions) through which to each virtual object (wall panel) must pass en route from pallet to placement. A user may adjust routing to include changes in path direction, translation speed and object (wall panel) orientation. Similarly, virtual humanoid workers can be assigned to the visualized assembly process with this interface. Virtual workers are assigned either to an independent work path or follow a specific object's (wall panel) work path through an inverse kinematics attachment. When the process paths for materials and workers are assigned for a completed assembly sequence the file is saved and the virtual model can be studied for further process analysis.

MACRO ASSEMBLY PROCESS ANALYSIS

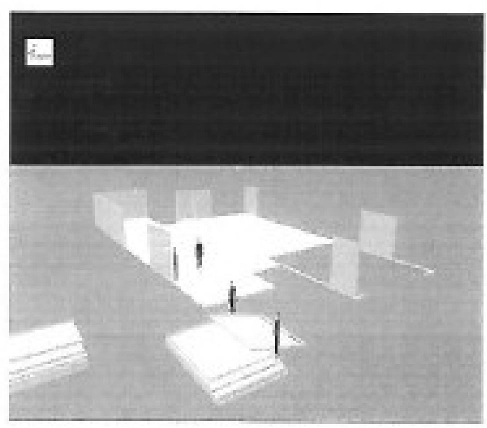
Staged Sequence

This assembly sequence starts with virtual workers pre-staging wall panels off-slab before wall panel assembly begins. Panels are pulled from top of the supply pallet and carried to their appropriate assembly location. Workers rest panels on the assembly surface with wall panel base plates typically facing the foundation/deck's edge face. Workers return to the pallet to retrieve the next top-pulled panel and the process continues until all exterior wall panels have been pre-positioned.



Random Sequence

This assembly sequence begins with workers pulling panels from the top of the shipping pallet. Workers match an embedded panel identification number with its proper placement position on the layout drawing provided by the panel manufacturer. Workers then deliver each panel to its corresponding chalk line position on the slab/deck. Workers complete a measurement, weather seal, fastening and bracing operation while securing an individual panel into place. Workers then return to the pallet for the next top-pulled panel and repeat the



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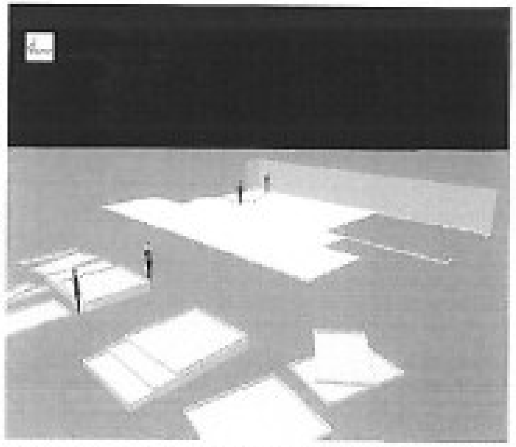
process until all walls are stood.

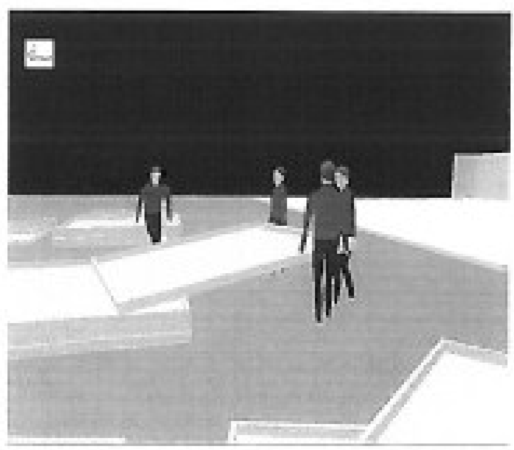
Discard Sequence



In this assembly sequence workers prefer adjacent panel assembly. Adjacent panels are identified on the layout drawing provided by the panel manufacturer. The appropriate alphanumeric panel is top-pulled with non-adjacent panels discarded onto secondary stacks near the delivery pallet. The first panel chosen for assembly (typically a corner panel) is set to its appropriate chalk-marked assembly position on the slab/deck. Workers will complete a measurement for the first panel in a wall section. Weather seal, fastening and bracing will also be completed before a panel is fastened to the slab/deck. The workers will then return to the pallet and continue the top-pull and discard process until arriving at the next adjacent panel. This assembly sequence continues until all walls within a specific wall section are completed.

MICRO ASSEMBY PROCESS ANALYSIS

Retrieval Sequence



When workers have chosen a panel for placement they begin to pull panels from the top of the delivery pallet. If the top panel is not the desired wall section, worker crews will discard it to an adjacent stacking pile. Palletized and sheathed panels over a certain size and weight may restrict a crew's ability to directly lift a wall section from the delivery pallet. Alternative lifting strategies are employed by either rotating the top panel some degree to allow for an opening of lifting positions at the corners, or by pulling a panel off the pallet itself. Once a wall panel is crew-sized and positioned for the lift, workers carry it to the appropriate assembly location.

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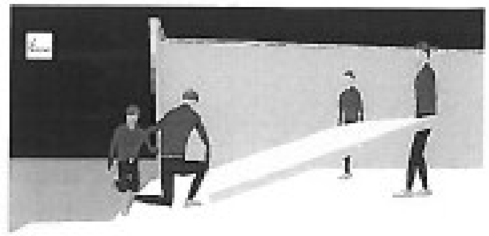
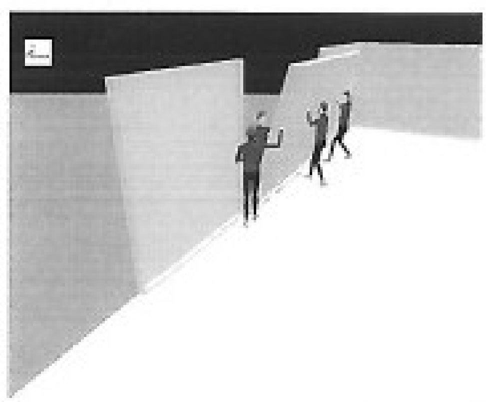
Preset Sequence



Work crews that have delivered a non-adjacent panel to its slab/deck position must measure for an accurate placement along the chalked layout line. The individual panel dimensions provided in the wall manufacturer's layout drawings allows workers to employ a tape measurement method providing distances from a known slab edge to a panel's start position along the chalked layout line. Panel-to-panel attachments require fewer measurements by a work crew other than accurate placement along the chalk line. Once a section's slab/deck position has been established it is typically laid upon the work surface and weather guard is attached. Foundation anchor holes are also drilled into appropriate panel base plates at this time. To identify anchor holes placement crews will typically pull panels snug to the embedded slab/deck bolts and scribe the drilling location onto the wall section's base plate. A second anchor measuring method employs two workers; one crewmember to measure the actual anchor bolt position in relation to a known edge while the other measures from the same start point, marking its corresponding position onto the panel's base plate. Anchor-bolt holes are drilled. Slab/deck anchors can be modified at this point if they are deemed to interfere with a wall panel's structural integrity. Polystyrene weather seal is typically placed between the panel and the slab/deck. This material can be pre-run along a chalk lined length of foundation, or individual lengths of weather seal can be cut and individually attached as panels are brought to an assembly location. From this point the panel is ready to be set.

Placement Sequence



Workers typically lift lighter panels directly into position along the slab/deck chalk line. The wall panel is stood and tooled into a flush position along this line. Similar tooling in the horizontal plane is provided as necessary to achieve a tight vertical connection between existing panels. If panels are large they may be tilt-set perpendicular to the deck/slab and slid into position (anchor bolts allowing). Again each panel is typically tooled flush along the slab/deck chalk line and vertically plained and tightened against an existing wall panel. One worker typically steadies the set panel while another nail attaches base and side plates to the slab/deck and existing wall sections. 2x4 lumber panel bracing is attached at this time. Final wall to slab/deck squaring is assumed through base plate contact. Finally, top plate additions, final wall squaring, and stabilization typically do not occur until all the wall sections have been composed upon the slab/deck.

Discussion

The completion of the preceding visualization framework affords the viewer a simulated comparison between each of the three distinct Macro level assembly methods and their corresponding Micro level assembly sequences. The application of virtual prototyping clearly illustrates those process differences, which occur throughout actual assembly but may be hidden within the larger production activity. Prototyped recognition of such process difference is exemplified in the Preset Micro assembly sequence shared by both the Discard and Random Macro procedures. A virtual comparison of the two Macro level sequences clearly exhibits that workers can shortcut required wayfinding and measurement activities contained in the Preset Micro, by reference existing "stood" panels in the Discard Macro, while functionally repeating entire Preset Micro sequencing for the Random Macro. It can be inferred from this comparison that the Discard Macro assembly would be the more efficient process; however, when each selected Macro assembly processes is virtually analyzed in relation to their Retrieval Micro sequencing, the selective-panel verses top-pulled placement operations ~~distort the claim for Discard Macro level assembly efficiency~~. can influence the efficiency.

FUTURE WORK

The logical next step for analysis of virtual construction process research is an ability to accurately measure perceived differences in prototyped assembly. Certain software tools provided within this study's sequence-modeling platform could begin to empirically inform and potentially verify selected comparative virtual analyses. The application of virtual assembly frameworks like those presented in this research can be programmed to model quantitative and qualitative outputs using the following existing software applications:

- Work Path / Time Sequencing Study - here assembly sequence procedures could be informed by real world data and expanded along virtual work routes thereby establishing a time of completion for each task. The results of this application could be used in combination with other prototyped Micro assembly tasks measurements to provide a cumulative duration assessments for an otherwise speculative virtual Macro assembly process.

- Endurance / Caloric Expenditure Study – here again Micro assembly sequence procedures could be empirically qualified using a Kcal Prediction Model provided within the virtual prototyping software. This modeler can estimate worker Kcal consumption for specific exertion tasks, which when applied to individual Micro assembly sequences could be used to construct a comparable predictive model for differing Macro level assembly sequences. Inversely, a less Kcal intensive work methods could be examined in relation to a virtual workers capacity to perform alternate Micro level assembly process, which could then be replaced within the Macro level assembly process to either increase or decrease the prototyped production efficiency.

- Ergonomic Lift Study / Work Path Interference - a lifting equation, the Recommended Weight Limit (RWL) established by the National Institute of Occupational Safety and Health, is applicable to the prototyped construction environment and can be used to measure human lifting capacity in a virtual ergonomic analysis (Deneb, 1998). In the assignment of risk factors to specific Micro level assembly procedures, a RWL within a specific worker's lift capability can be assessed in simulation. With this modeling capability a user can perform "what if" analyses by manipulating virtual object oriented parameters such as distance-to-work and object weight. Related work path adjustments can be made using the prototyping platform's object oriented collision awareness software. The implementation of object volume sweeps, collision and near miss tolerances should enhance those modeled assembly tasks that require material integrations. This proposed combination of materiality and ergonomics, could enhance the precision of any virtual process analysis.

It is suggested here that time, energy, and capability analyses of a virtual work task, establishes the baseline for a prototyped assembly lexicon. When basic construction tasks can be modeled and refined against competing assembly procedures in a virtual format, the beginnings of a calibrated prototype model for construction assembly activity is realized. It is envisioned that process information derived from such comparison will contribute to the overall quality of communication between design and production.

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6.1. B: ***Exploring a Virtual Modeling Hierarchy for Construction: Two Case Studies***

Exploring a Virtual Modeling Hierarchy for Construction: Two Case Studies

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Abstract

The conversion of actual construction events into virtual representation is a challenging task. Applying virtual modeling and simulation as an analytic and predictive tool for construction planning is an even greater challenge. This paper explores some of the difficulties faced and suggests a modeling hierarchy developed with virtual programming experience gained from two construction assembly case studies.

Keyword:

Construction process modeling, assembly simulation, virtual prototyping

1. INTRODUCTION

The construction industry has historically maintained a dynamic production environment as compared to manufacturing. Despite and perhaps because of this fact, the Architecture, Engineering and Construction (AEC) industry has long been interested in the quality and process efficiencies realized by other industry manufactures such as automotive and aerospace. Recent AEC trends toward concurrent engineering and the use of premanufactured building components has led to an increased interest in production simulation. A component of this focus had centered on the virtual prototyping of construction process and product lifecycle. This paper explores a hierarchical approach to virtual construction simulation by addressing complexity and fidelity challenges present within two separate AEC manufacturing environments.

Virtual modeling is far from new to an industry with a growing body of research related to abstract and discrete modeling. Simulation has been widely applied by academia to construction. Construction simulation and modeling efforts include Petri nets (Wakefield, 1999), CYCLONE (Halpin, 1977), RESQUE (Chang, 1986), GPSS (Schriber, 1989), COOPS (Liu, 1991), DISCO (Huang and Halpin, 1994), and STROBOSCOPE (Martinez 1999). Researchers have also focused on visualization to examine construction process (Fischer and Kam, 2002). With industry pervasive Web-based interconnectivity and the standardization of CAD-type project platforms, an attempt is being made by the AEC industry to achieve production benefits realized in the manufacturing engineering and materials management disciplines. Their industrialized successes, built on visualization methodologies and concurrent-engineering principles, is typically envisioned for construction as a transparent project communication framework linking client requirements, design, engineering, and supplier databases, to contractor and facility management implementations. (Kamara and Anumba, 2000; Jang and Eastman, 1999; Anumba and Evbuomwan , 1997). An example of such efforts can be found in Industry Foundation Classes (IFC) that are, at present, attempting to build an ubiquitous communication framework from divergent forms of AEC production and simulation softwares. (Fischer and Kam, 2002; Bazjanac and Crawely, 1997).

While this paper does not intend to investigate application interconnectivity for construction process modeling, it does approach a method for modeling the dynamic AEC environment which can confound the virtual reconstruction of on and off site assembly processes. The findings of a recent independent report on the achieved benefits and return on investment using a leading digital manufacturing simulation platform suggest that "to gain maximum benefit, digital manufacturing software should be implemented as a component in an end to end, comprehensively integrated product lifecycle management solution" (CIMdata, 2003). When considering facility design and construction process in America, the AEC industry's effort is still dominated by a non-concurrent and fragmented approach far from this idealized situation; however recent industry focus on premanufactured construction components is attempting to reduce production challenges with industrialized product engineering.

The actual creation and field implementation of pre-engineered materials provides an excellent opportunity to address what this paper feels to be the initial challenge facing construction simulation, that being the accurate characterization of processes within a seemingly asynchronous and overlapping work environment. The proposed hierarchy will examine the importance of assembly process recognition for accurate simulation of construction situations. This paper also addresses a converse challenge to construction prototyping, that being the capacity of simulation programming to accommodate assembly information as virtual process. Many of the simulation industry's customized approaches to prototyping can challenge the novice programmer intent on virtual replication of complex environments. These challenges highlight the need for a virtual construction modeling hierarchy fashioned from an approach to programming capacity and industry specific assembly situations.

2. VIRTUAL CONSTRUCTION MODELING HIERARCHY

This paper addresses the challenges presented by construction process complexity and simulation programming capacity. A virtual construction modeling hierarchy is developed from experience gained on two industrialized construction case studies. Both case studies have been well documented by the authors and utilize a detailed set of production data that is not readily available in most virtual construction modeling situations. (O'Brien et al, 2002) The five phases of virtual construction hierarchy detailed below are a result of this and other similar construction process research. (See Figure 1)

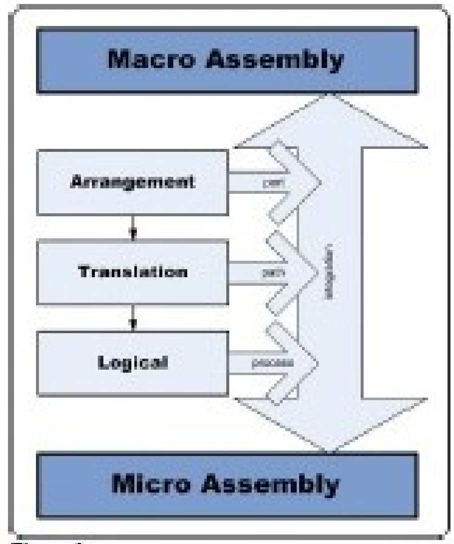

Figure 1

2.1 Macro assembly modeling

Macro assembly modeling begins with the identification of a construction sequence. In the real world environment a macro assembly sequence can be characterized by the application of a specific building system or the depletion of a specific resource stock. Similar macro model definition could identify work progression or task repetition over an established time frame. An example of a defined macro assembly sequence would be the field completion of a panelized wood stud wall system. (See Figure 2) The prefabricated wood stud wall, or "panelized" system, presents an alternative to traditional wall creation. Wall panels are designed and fabricated off site, with sheathed and unsheathed conditions possible at delivery. Wall sizing is typically dependant on installation weight, shipping dimension, and structural integrity. Wall suppliers typically provide contractors with a wall placement plan which references foundation locations using numeric identification indicated on each wall panel.


Figure 2

6.1. B: *Exploring a Virtual Modeling Hierarchy for Construction: Two Case Studies*

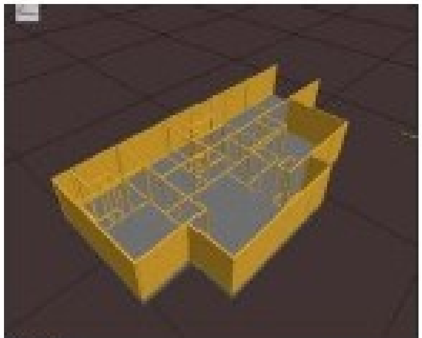
Figure 3

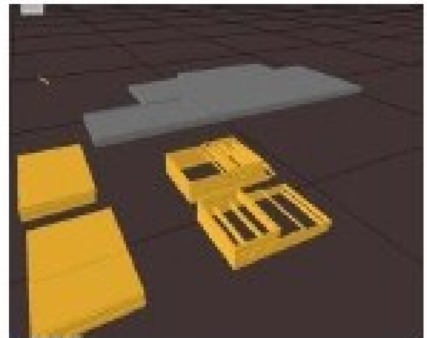
Figure 4

The panelization process begins with a foreman's dimensional layout on the foundation slab to identify panel placement positions. For the simulated case study, the macro assembly sequence begins with this dimensional layout task completed. The exclusion of this real world process within the virtual environment accomplishes two things: first it denotes a clear process boundary for macro assembly modeling, and second it associates dimensional layout activity as an operation within the foundation macro sequence. Macro assembly modeling therefore identifies the moment prior to a panels removal from the supply pallet as a starting state for the panelized process. Conversely, the delivery of all wall panels to their final standing position represents a clear end state for the macro assembly sequence.

Macro assembly modeling recognizes both end states of this linear process as an assembly boundary. The virtual definition of macro model boundaries requires that only those elements necessary to the simulation process populate the environment. For this case study, macro assembly modeling requires the importation of 3D CAD wall parts to populate the simulation environment. Similarly, the slab foundation was imported with a dimensional overlay provided by the panel manufacture, to facilitate end state panel positioning. It should be noted that the graphical simulation software employed in this case study does not require operational elements such as labor or lifts to be present for initial parts motion programming. Similarly, representation of tooling or bracing is not required at this level of the hierarchy.

2.2 Arrangement Phase

The arrangement phase of panelized construction is defined by a wall panel in either of its end state positions, as identified by the macro assembly sequence. When construction begins individual supply pallets are moved near or directly onto the foundation slab depending on site space characteristics and chosen production methods. A pallet's physical location and internal panel sequencing suggests actual wall assembly order. The virtual component of arrangement phase modeling focuses on recreating a part's end state positioning within the simulated environment. Macro modeling can populate a completed 3D CAD wall assembly into the virtual environment. (See Figure 3) Conversely panels can be imported into the model in their palletized form. (See Figure 4) For both of these cases each individual wall panel enters the virtual model pre-translated into one of its two possible end states. Typically macro assembly modeling will populate virtual parts into the simulation environment with arbitrary positioning. In this case, a programmer will arrange all model parts into their respective end state positions using the simulation platform's interface

The arrangement phase of the virtual modeling hierarchy highlights the importance of identifying the scope of a macro assembly sequence. The end point boundary positioning of affected virtual parts empowers a simulation programmer with a formalized scheme which informs future phase programming. This virtual framework will be used to connect translation pathways and define a parts logical sequencing in the following two phases.

2.3 Translation Phase

Where the previous arrangement phase framed an initial formal logic for simulated assembly, the translation phase creates the infrastructure for functional operation. The translation phase uses two main modeling elements to do this: paths for part routing and activity points for functional attachments. Path creation defines the linkage required for a part's end state translation through the established macro assembly sequence. Virtual activity points

6.1. B: ***Exploring a Virtual Modeling Hierarchy for Construction: Two Case Studies***

Figure 5

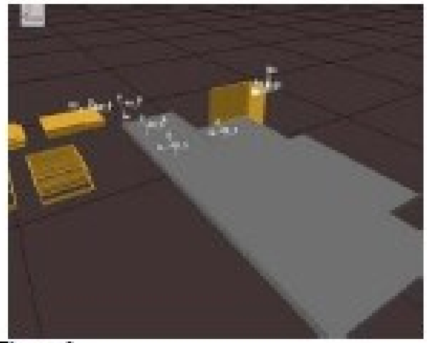

Figure 6

indicate nodes of potential interaction for simulated parts and elements. Within the macro assembly sequence actual panel motion begins with a specific number of workers dislodging one panel from its end state position. Larger panels are carried, typically horizontally, to a set down point and then tipped into final placement position. A delivery route may rotate a panel in any of three axes to aid in the lift, avoid obstacles, and establish the end point assembly position. (See figure 5) Final positioning typically adjusts for panel to panel and panel to foundation connection and signifies the completion of the panel translation phase.

Virtual assembly translation requires a simulation programmer to indicate a part geometry attachment point for path creation. Path creation can then occur by setting points within the virtual environment. (See Figure 6) Path creation by direct manipulation of the 3D part within the virtual environment is also possible. A combination of these two approaches is typical if both end state positions have been identified. A programmer can position parts at known end point locations and then infill with translation nodes to form the assembly route. When completed, the assembly path will comprise appropriately oriented and located points through which an associated panel part must translate.

Most virtual model elements receive and carry attached activity points in the translation phase. Point attachments to individual part geometries are a fundamental component of part orientation and alignment. Without these nodes, the exact translation of virtual part geometries would be impractical. Similar points define where and how operational elements, such as labor, attach to parts within the model. For example, a simulation programmer can assign attachment points to panel geometries where known lifting locations should be represented. Labor elements can be directed to grab at an activity point within its reach or arrive to its location when called.

Ultimately the impact of translation phase programming on overall simulation fidelity is dependant on data set quality and macro model detailing. For this case study the programming technique attempted to link a part's end state positions and then modify a path to match its observed trajectory. Nodes along the trajectory path allow a programmer to snap parts between points to visually check positioning. Translation paths and activity point attachments can be created for most model elements; however for this case, operative elements such as labor will borrow panel routings in later translation phase integration.

2.4 Logical Phase

The logical phase of virtual modeling hierarchy attempts to mimic real world assembly form and functionality using integrated programming. Actual assembly activity, like the wall panel to anchor bolt connection, proves difficult to program using virtual part manipulation alone. Most simulation platforms without an advanced geometric interference capacity will allow virtual parts to pass through one another during translation programming; however real panel placement must respect the physical constraints inherent to a wall translation over and around a foundation anchor bolt. Similarly, a nut or nail attachment may not arrive at an end state position before the panel to foundation translation has been completed. An accounting of assembly necessity created by actual physical and procedural interferences must be programmed using the logical interface of the simulation platform.

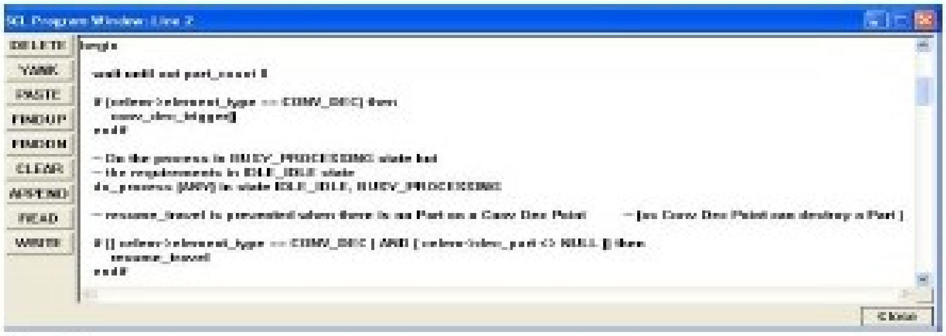

Figure 7

The logical interface coordinates information defined in the previous part arrangement and path translation phases. This can be seen in the logical assembly programming for wall panel delivery at the supply pallet. For this case, delivery order is defined by the palletized order. Again, most graphical simulation interfaces do not recognize geometry-based interferences without a robust processing capacity, so the virtual order of part lifts must be defined using logical rules. A programmer refers to both the formal ordering established in the arrangement phase and the translation routes which lead from each panel to an end state assembly position. With this information a programmer infers a logical sequence for delivery simulation that mimics actual process.

The primary tools in logical virtual programming are part and path assignments, time sequencing, and property status designation. The activation of part motion along a path is a basic logical assignment. Functional orders can be choreographed sequentially or digitally synchronized using an input/output signaling system. The independent motions of two coordinated labor elements working on intersecting activities would be an example of the latter type of programming. Equally common are features which assign individual or grouped parts motion along a single path, as is the case in palletized motion. A related logical interface controls attachment and detachment status. An example of this programming would be the attachment of a tool part to a virtual worker's hand. An ability to cue part visibility is also a key component in logical simulation programming. The appearance or disappearance of parts during a simulation is an indispensable programming shortcut. Directional control over individual path routing is another key feature to logical simulation. The ability to reverse sequence completed part assemblies is a great programming advantage, as simulated linear work progressions are bidirectional.

Ultimately, the functional orchestration of model components is an important factor deciding a virtual prototype's fidelity to actual process. While a considerable amount of logical part coordination can be handled through the default interface, an open-ended Simulation Control Langue (SCL), expands programming capacity for more complex process modeling. (See Figure 7) This programming language provides the simulation programmer with a flexibility to functionally match any geometry to most virtual assembly situations.

2.5 Micro Assembly Modeling

The micro assembly modeling phase further defines a selected frame of the larger macro assembly model. Input from detailed process and product data refocuses part arrangement, translation, and logic phasing associated with the macro assembly sequence. For example, micro assembly modeling could focus on the identification of lifting points used by labor during a panel's translation. (See Figure 8) Additional site information would supplement existing lift points first established in the translation stage. A programmer can add or

Figure 8

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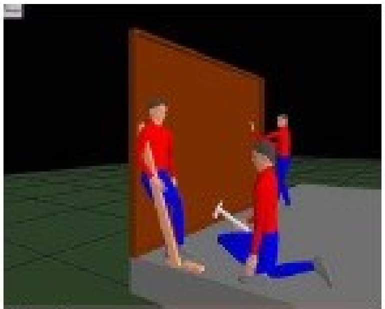
Figure 9

relocate lifting points that correlate with known translation positions and logical part connections. This type of micro assembly definition ensures that an addition of labor or tooling will intersect precisely within the panel's simulation. When this method of micro assembly refinement is applied to ergonomic capacity and task efficiency a more accurate and potentially predictive simulation can be expected.

Micro assembly modeling focuses on adjusting affected hierarchical stages to enhance the macro assembly sequence. An example of micro assembly adjustment would be the addition of labor elements to a simulated wall panel assembly. The addition of labor elements will require the input and adjustment of existing macro part arrangements, translational and logical phase elements. Macro level redefinition will result from labor's own hierarchical limitations defining endpoint positioning (e.g. posturing), path routing (e.g. reach), and logic (e.g. grab and release) required to stand a single wall panel. (See Figure 9) Additional micro modeling detail such as hammering postures per panel will inform task-time allotments in the larger macro simulation sequence. Similar definition of individual labor routing will logically coordinate labor tasking within the macro assembly model. A second standalone approach to micro assembly modeling should be mentioned. This technique defines and validates a separate assembly sequence found within the macro assembly model. This type of micro modeling is created with hierarchical phasing, yet is typically limited to cyclical activities found within a macro assembly sequence. An example of this application is the scripting of a laborer's posturing during repetitive hammering activity. The worker's motion is first defined by a panel assembly sequence. Once the hammering motion is captured it is saved as a script file. This file is then combined with the larger macro panel assembly sequence using the logical interface. Playback of compiled micro assembly models minimizes computer processing burdens in large macro model simulations.

3. INDUSTRIALIZED CONSTRUCTION COMPONENT CASE STUDY

This paper's second case study highlights the simulation of a slightly different industrialized assembly operation. Also, the software used for this simulation resides on a different suite of the same parent modeling platform employed in the previous example. The slightly different approach to both the virtual and actual modeling environments is intended to suggest the applicability of the virtual modeling hierarchy. Figure 10 illustrates separate work cells located within a factory's concrete wall production line. Individual work cells contribute reusable metal formwork in a specified structural layout fixed to mobile work platforms. Each mobile work platform with its formwork will encounter concrete casting, curing, stripping, breakdown, and rewash processing within the production cycle.

3.1 Macro Assembly Modeling

Figure 11 represents the entire wall assembly operation as it was first populated within


Figure 10

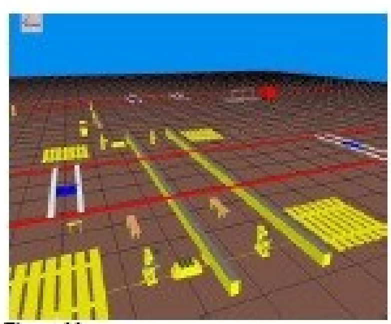
Figure 11

6.1. B: ***Exploring a Virtual Modeling Hierarchy for Construction: Two Case Studies***


Figure 12

the virtual environment. Default software elements are selected which represent the approximate functional and logical capacities encountered within each work cell. The list of default elements populating the larger macro assembly model includes: cranes, conveyors, lifts, buffers, and machines. The population of functionally accurate elements is directly tied to the framing of the macro assembly sequence.

For this example, the end state assembly boundary associated with concrete formwork (i.e. bulkheads) has been chosen for simulation. (See figure 12) Activity in that work cell encompasses the removal of formworks from a supply buffer and its placement onto a mobile platform. The identification of a macro assembly sequence requires the population of only those elements essential to this process: a machine, a buffer, and a crane. These three elements along with two part elements taking the form of bulkheads and the work platform define the macro assembly sequence. It is again noted that the graphical simulation software employed in this case study does not require operational elements such as labor to be present for initial parts motion programming.

3.2 Arrangement phase

The arrangement phase focuses on the formal

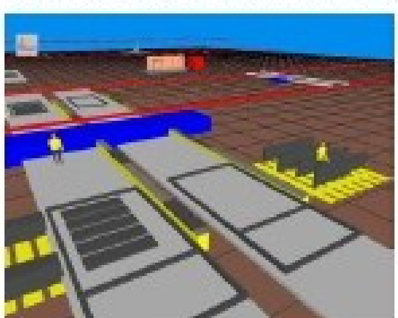
Figure 13

compositional requirements of a macro assembly sequence. The physical location of stacked bulkhead formworks represents one end state boundary to be graphically programmed. Similarly, the fulfillment of a formwork layout represents the other macro assembly boundary. Defining the specific assembly sequence is only possible after default model elements have been replaced with the CAD based iconic representations. In this case, geometrically accurate icons representing workstations, mobile platforms and formwork parts were applied to default elements. A CAD icon showing pre-stacked formwork positions within a buffer was imported to assist with end state arrangement of bulkhead parts. Conversely, an icon representing a mobile work platform with its completed bulkhead layout was also imported into the virtual environment at this time. The virtual recreation of observed end state assembly boundaries completes the arrangement phase. (See Figure 13)

3.3 Translation Phase

The translation phase establishes connections for functional operations between model elements. Part motion and logical command connections shared between elements must be programmed in the virtual environment. For this example, the bulkhead part delivery will require a linked connection through a crane element. Logical connections must also be established between elements which require signaling to begin assembly processing. Activity point nodes must also be defined to collect parts at established locations.

Figure 14 highlights the part route linkage through the buffer, crane and work platform elements. The figure also illustrates activity points which are affixed to the work platform and guide the incoming formwork into its prearranged layout. The placement of activity points underscores the importance of defining

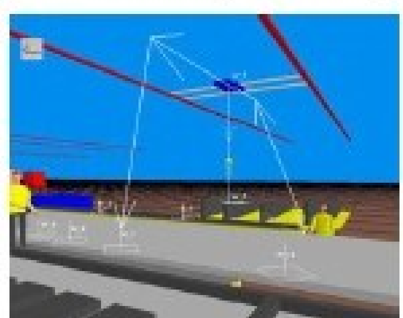
Figure 14

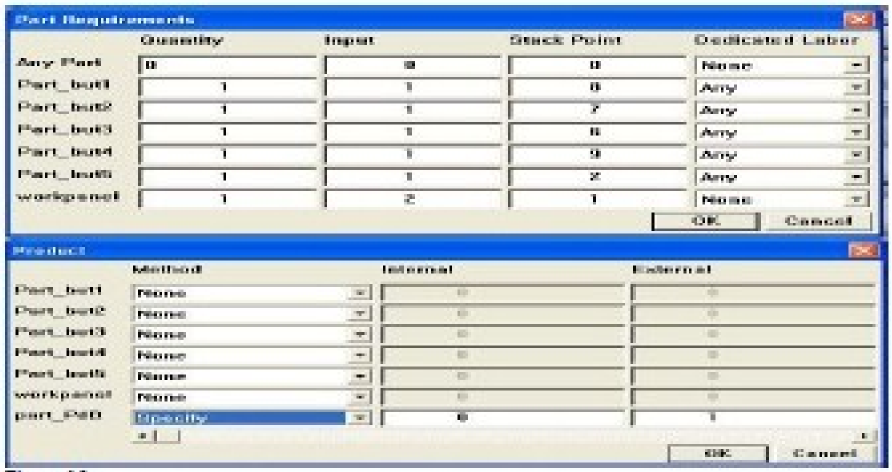

Figure 15

end state assembly positions within the macro sequence. The assignment of element icons representing end state part positioning considerably shortens translation phase programming time. A programmer can use the completed formwork pallet icon shown in Figure 13 to locate and orient bulkhead delivery nodes seen in Figure 14. All icons, nodes, and pathways can be visually turned off prior to the actual simulation run using logical controls discussed in the following phase.

3.4 Logical Phase

Where linkages established in the translation phase provided the pathways for process requests and parts translation, the logical phase defines the message being sent. Using information derived from the real world assembly scenario, a programmer can compose formal part arrangements and translational path alternatives which will replicate the activities observed within the macro assembly sequence. For this case, logical programming begins with the arrival of a mobile work platform to the work cell.

Upon arrival of the platform part onto the holding machine element, a bulkhead part request is made to the linked supply buffer. The logical interface can prescribe: the request path, the type and number of part needed, and which activity node will receive a delivered part. Upstream buffer elements that receive this request must also be programmed with a compatible logic. This programming can specify: inventory control and batched delivery, acceptable input and output pathways, and require a labor or crane element for part movement. Each model element offers multiple logical applications and it is the job of the programmer to synchronize their utility for an effective simulation run.

The logical interface used to program a machine's processing of work pallet and bulkhead parts is illustrated in Figure 15. From the figure it can be seen that the machine's part requirement logic specifies part numbers must arrive through selected inputs (paths) and be delivered to prescribed stack points. (activity points) When the part delivery request has been fulfilled a machine begins its processing mode. For this simulation, all delivered parts are instantaneously destroyed except for the work pallet, which graphical icon is simultaneously replaced with a single CAD representation (part_PdB) depicting the complete bulkhead layout. This process logic alternative was chosen for its routing simplification. The processing and group passage of individual parts is also possible; however, higher part count models require greater computer capacity during large simulation runs.

3.5 Micro Assembly Modeling

For the novice programmer, logical phase definition can require considerable planning to model simple assembly situations. Framing the macro assembly sequence, its arrangements and translation phase elements can however aide the selection of logical assignments necessary to affect a stable macro simulation. From this

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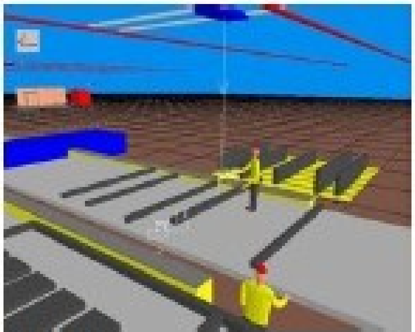

Figure 16

point, micro assembly modeling provides the programmer with an opportunity to enhance assembly procedures using the filtered clarity provided by defined hierarchical events. Micro assembly modeling integrates detail into the simulation model through the addition of elements and processes that were not completely addressed by the macro sequence.

An example of sequence refinement would be the attachment of a labor element to the part delivery process. (See Figure 16) The macro assembly sequence was initially created to function successfully without labor attachments. The inclusion of labor into the sequence requires a programmer to integrate that element's characteristics into the existing simulation. Each affected phase of the macro assembly sequence must be adjusted to the additional worker data. The scope of labor's interaction within the macro assembly sequence must first be identified. This distinction informed the question as to whether the programmer should define basic labor motions between elements or detail an ergonomic assessment for one particular assembly. The arrangement phase formally defined that scope by generating appropriate ergonomic postures which ensured interaction with a part's end state positions. Translation phase programming created acceptable labor paths which can closely parallel or directly borrow from a part's routing. Activity points were assigned to model elements (e.g. crane hoist) to established reaching and contact points for later ergonomic posturing consideration. Finally, logical element programming was used to define physical states such as grab and release, and to synchronize motion between parts, crane, and laborer elements.

4.0 Conclusions

The virtual modeling hierarchy suggested by this paper is an initial attempt to conceptualize the dynamic nature of construction simulation. The suggested methodology is the combined product of initial experience gained on a flexible virtual simulation platform informed by industrialized assembly process. Its approach was based on the attempt to bridge both programming capacity and comprehension of assembly detail. The resulting experience found that even with the clarity of industrialized production, accurate simulation of basic assembly procedures can require a considerable investment in both time and effort. The resulting classifications of the hierarchy suggest pertinent protocol approaches which seem common to both the industrialized and simulated assembly scenarios. It is proposed here that issues of work scope, part arrangement, pathing, and sequencing comparatively translate between the real and virtual assembly environments. Development of a virtual modeling hierarchy should attempt to further clarify similarities in the cross field orchestration of part assembly. It is suggested that only when this connection is sufficiently framed in a clear and functional manner, can virtual prototyping accurately portray itself as the analytic and predictive tool sought by the AEC industry.

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Auburn Hills , MI. USA

6.1. C: *Icon-Based Prototyping for Construction*

ICON-BASED PROTOTYPING FOR CONSTRUCTION

Brendan A. Johnston [1], Yvan J. Beliveau [2], and Ron R. Wakefield [3]

ABSTRACT

This research proposes a new method of prototyping industrialized construction process using a digital process/product modeling (DPM) programming hierarchy. An icon-based methodology for conceptualizing assembly is presented using field data collected from the installation of a precast foundation wall system (PWS). This effort develops a graphical heuristic for industrialized assembly and suggests a new taxonomy for designing construction operations and presenting those designs to the field.

KEY WORDS

icon programming, assembly prototyping, industrialized construction.

INTRODUCTION

Beginning in the 1970's, Japan's shift toward quality-based industrialization of home production attempted the control of a diverse product line in a dynamic delivery environment (Gann, 1996). At present however, even within the factory controlled settings of manufactured housing (e.g. HUD Code homes) efficient production has been slow to advance (Mehrotra, 2002). Concurrently but separately, computer simulation tools for modeling construction activity have also developed over the same three decades, (Halpin, 1977; Paulson, 1978; Chang, 1987; Ioannou, 1989; McCahill and Bernold, 1993; Martinez and Ioannou, 1994; Huang et al., 1994; Sawhney and AbouRizk 1995; Martinez 1996; Wakefield, 1998; Shi, 1999; Zhang et al., 2002). Many of these construction simulations have advanced alternate methods for defining work flow, unit activity, and resource utilization. Their practical application to the construction industry has however been minimized, in part, due to issues of implementation cost, usability and applicability, (Halpin and Rigs 1992, Halpin and Martinez, 1999; Shi and AbouRizk, 1997).

Other manufacturing industries have evolved with sympathetic simulation of their design and production processes. (Albastro et al. 1995, West et al. 2000, Kirbira and McLean 2002) One software type used for aerospace and automotive applications is the digital process/product model (DPM). This approach integrates discrete activity modeling with an animated simulation tool. Programming can model actual best practices within a virtual environment capable of assessing real-world physics and ergonomics. A DPM approach is

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leveraged by this research to create a prototyping hierarchy which can effectively illustrate industrialized construction assembly.

INDUSTRIALIZED CONSTRUCTION

The US residential construction industry has also begun to increase its reliance on site-based assembly of premanufactured components; it has been proposed that this move introduces building systems that require fresh approaches to traditional design and delivery methodology (O'Brien et al. 2000, 2002; Wakefield et al. 2001). If industrialized residential construction is to maximize its efficiency, a functional heuristic for analysis and communication of onsite assembly must be developed. While there has been early development in the technologies associated with industrialized residential construction, there is to-date little specific research in the area of modeling the information relevant to its onsite production. (Senghore et al.2004; Johnston et al. 2004; Wakefield et al. 2003).

Production information for this task can be found by examining the assembly processes of a precast concrete panel wall system (PWS). Structural wall panels are fabricated within a factory environment employing CAD/CAM dimensioning and lean manufacturing processes. The wall's structure and integration design is pre-engineered to facilitate onsite construction. Panels are shipped to the construction site where they reside on material skids prior to the foundation's start. Wall panels are lifted by crane into their final assembly position where workers apply parts and resources to complete the installation (Figure 1). On-site assembly schematics are typically limited to a basic site plan indicating wall dimension and relative positioning.

Figure 1: Precast Panel Wall System

ASSEMBLY DEFINITION

When construction activity is examined its composite assembly process, material and resource requirements become apparent. This composition is rarely illustrated as a procedural schematic, with assembly information typically left undeveloped or omitted. It is posited here that a clear compositional definition of an assembly boundary assists efficient industrialized construction (i.e. a tested work sequence connecting two PWS panels). Furthermore, industrialized construction can be conceptualized as a collection of assembly boundaries (Figure 2). Therefore, the composition of an assembly boundary can be characterized using a DPM type accounting of actual parts, processes and resources necessary to create an efficient production interface (Figure 3).

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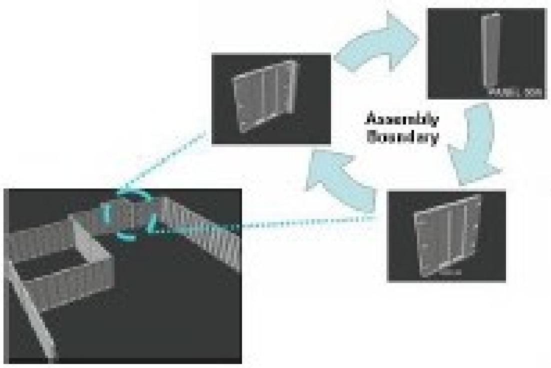

Figure 2: PWS Assembly Boundary

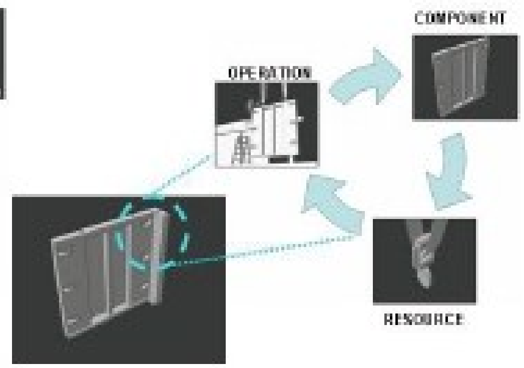

Figure 3: DPM Boundary Characterization

PROTOTYPING APPROACH

This research leverages a programming hierarchy provided by Dassault System's Delmia V5 Digital Process Modeling Suite to characterize assembly boundary composition into Operation, Component, and Resource windows. Production data used in this approach comes from an observed panel installation sequence (see Appendix). The diagram in Figure 4 depicts the activity frame used to describe each tasks in the PWS assembly sequence. Operation, Component, and Resource windows within an activity frame hold constituent icons attributable to the task. Each frame is also identified by its verbal definition and numerical position within the assembly sequence.

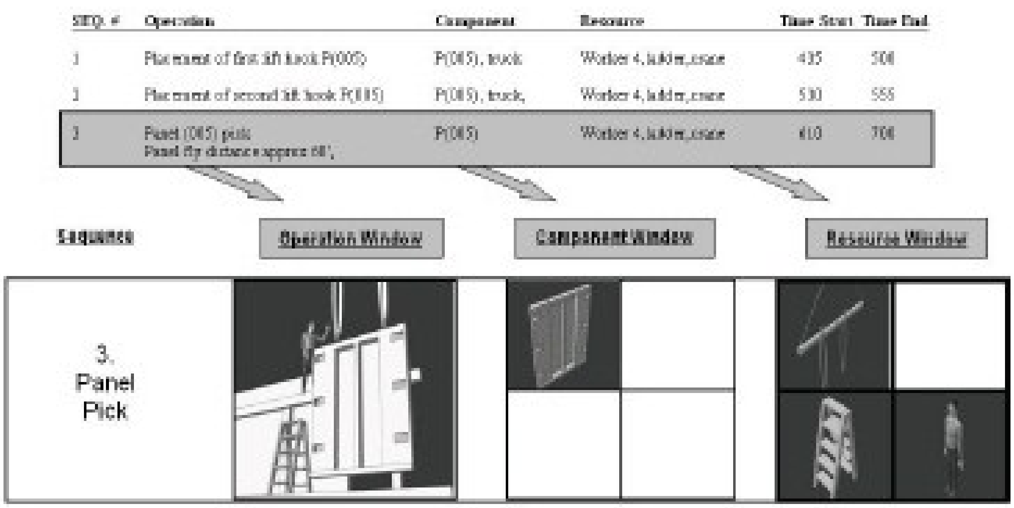

Figure 4: DPM Influenced Task Activity Frame

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Operations window

The Operation window depicts the assembly process associated with the construction task. As an example, the Operations window for the Drill Middle Hole task illustrates a worker holding a tool to its work position (Figure 5). Presently, the still-frame animation format requires that the Operation window be constrained to a single representative image; as such it is noted, that sub-tasks associated with a highlighted operation may not be illustrated in-frame (e.g. the use of a screwdriver to clear the drill-hole prior to bolting). Iconic sub-task recognition and its categorization will be discussed in a later section of this paper; initially however, process representation within the Operation window reflects the task analysis made during construction sequencing.

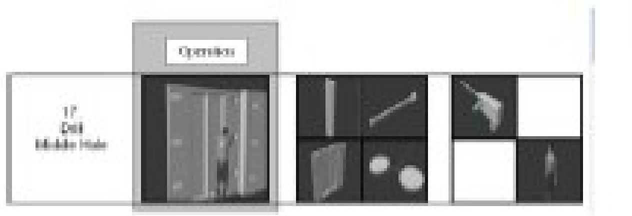

Figure 5: Operations Window

Component window

The Component window identifies assembly boundary parts which are relevant to the highlighted task. Only those parts which actively contribute to the product are identified by icon in the window. For example, the Panel-Pick task highlighted in Figure 4 illuminates the panel icon and not the material skid within its Component window. This subtractive task is defined at the beginning moment of panel/skid separation and completes the panel/crane assembly product. Furthermore, Component window icon recognition requires that all parts must actively contribute to the end-product of the specified task. An example of icon addition to a task's end product can be seen in the Bolt Middle Hole Component window where the top left bolt icon indicates final fastening (Figure 6).

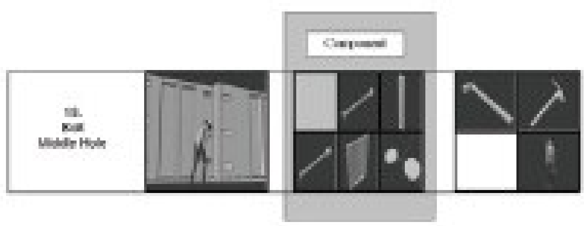

Figure 6: Component Window

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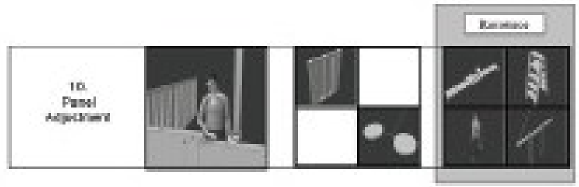

Figure 7: Resource Window

Resource window

The Resource window illuminates resource icons active at any time during the defined task. Resources can remain active over sequential tasking and their continued presence within the Resource window represents utilization. An example of resource utilization is shown in the Panel Adjustment task (Figure 7). The Resource window illustrates the application of a panel winching device, identified by its graphical icon in the top-left corner of the matrix. The winch icon remains highlighted in all subsequent frames for which it is engaged. Logically any task directly following winch removal will not contain the winch icon in its matrix, if it is not utilized.

As previously mentioned, sub-tasks may not be recognized in the activity frame's Operations window; however, icon presence within a Resource window matrix may suggest a sub-task. Figure 8 gives a resource accounting of potential sub-tasks that may otherwise be omitted or left un-illustrated as an operation. The task's operational image omits the potential hammer insertion of an expansion bolt into a drill-hole. The hammering activity did not rate its own task definition within the assembly sequence and was omitted as a sub-operation; however, the Bolt Bottom Hole Resource window may contain the hammer icon associated with that sub-task.

WINDOW MATRIXES

The composite structuring of icon windows strikes a functional and analytical compromise between animated and still-framed prototyping. A rule-based formulation of icons within Component and Resource windows can suggest highlighted tasks through positional cues. For example, when a window is read from bottom right to top left resource implementation order during tasking can be suggested (Figure 8). Similar iconic association within the

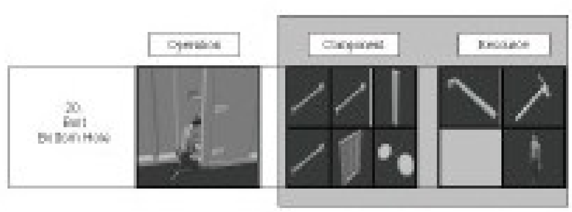

Figure 8: Composite Window Matrixing

windows of sequential tasks could suggest continued utilization of a specific tool by a laborer, or highlight a new resource requirement.

A Component window also provides a snapshot of actual construction methodology and shows its potential as a construction heuristic. Iconic ordering within the matrix can graphically represent part composition and procedural order at the assembly boundary. A Component window showing foundation pucks, panel 5, first bolt, panel 4, and remaining bolt icons illustrates a completed wall sub-assembly (Figure 8). Examination of this icon composition illustrates a panel–bolt–panel adjacency relationship. While the relationship was achieved earlier in the assembly sequence it signifies the first moment of mechanical connectivity between two wall components. The presence of this icon pattern in any subsequent activity frame indicates a "Stable-state" at the assembly boundary. State recognition allows alternative tasking based on the preferred construction management practice: bracing, released crane utilization, or the start of a new sub-assembly (Figure 9).

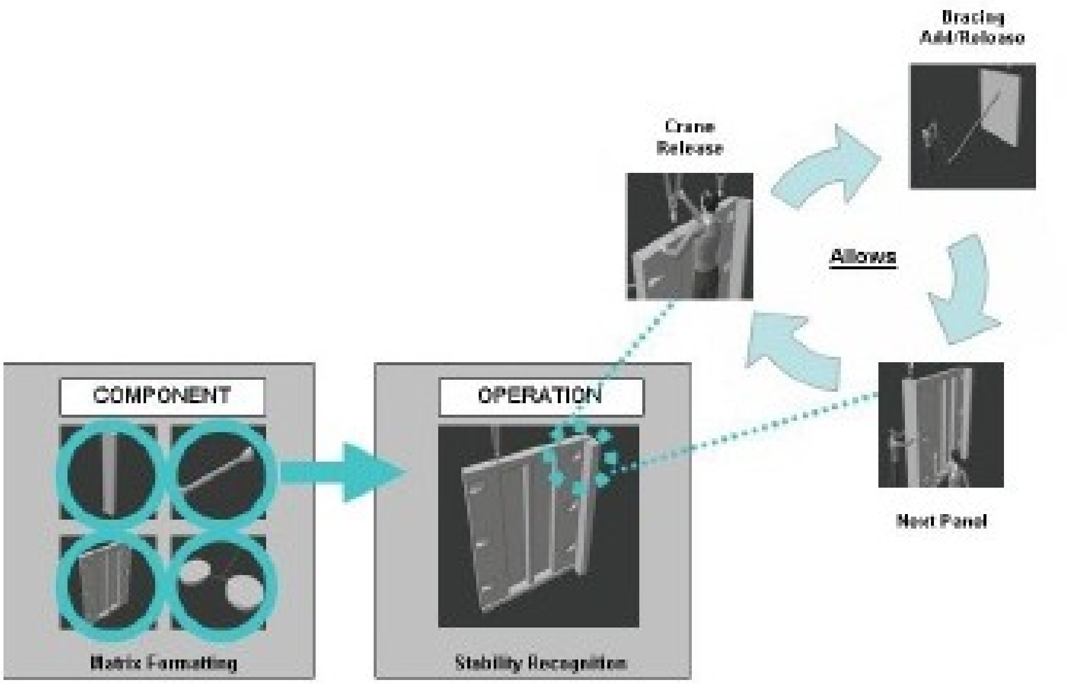

Figure 9: Iconic Production State Recognition

CONCLUSIONS / FUTURE WORK

This research develops an icon-based methodology for construction prototyping and suggests how task specific assembly information would be formatted. Where a DPM approach uses logic and visual based programming to prototype assembly process, a rule-based translation of that programming can inform and validate most construction activity. The task matrixing illustrated within this paper suggests how iconic representation can model an industrialized assembly boundary. The research purposes that still-frame characterization of assembly sequencing can provide a graphic constructability analysis pertinent to industrialized construction techniques and technologies.

It is recognized that before icon-based assembly prototyping can accurately describe the full spectrum of encountered construction activity; a richer taxonomic definition of actual assembly procedure must be developed. An important step toward this goal will be the standardization of rules that definitively matrix observed assembly, with traditional construction simulation challenges related to dynamic processes and definitive sequencing being addressed. Solid classifications of task verses sub-task, and assembly to sub-assembly relationships should be justified. Furthermore, matrixing should explore the relationship between the suggested method's format and capacity for user comprehension (i.e. fidelity). The importation of animated procedural clips within an Operation's window is one such example. Three dimensional (3D), virtual reality modeling language (VRML) icon expression of actual construction processes, resources and components is another.

Ultimately, future work should suggest how iconic prototyping will empower the broader spectrum of construction understanding. The development of an icon-based construction analysis/assembly nomenclature (ICAN) would provide a definitive categorization of construction assembly. The question of how a prescriptive graphical language applies itself to the overall production hierarchy should be asked. As a first step, this research highlights the developmental framework for iconic prototyping of industrialized assembly and suggests its potential as an effective illustrator of actual onsite construction procedure.

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NOTE: All graphical simulation figures courtesy of Dassault System's Delmia V5 Digital Process Modeling Suite., 2003 Delmia Corp., Auburn Hills. MI. USA

6.1. C: *Icon-Based Prototyping for Construction*

Table 1 gives written example of field data collection and formatting for a single wall panel.

Panel III (005)

SEQ. #	Operation	Component	Resource	Time Start	Time End
1	placement of first lift hook P(005)	P(005),truck	Worker 4, ladder,crane	455	500
2a	placement of second lift hook P(005)	P(005),truck,	Worker 4, ladder,crane	530	535
2b*	Drill hole for middle flange bolt **See previous P(004)			515	530
2c*	Place Expansion bolt **See previous P(004)			515	610
3a	Panel (005) pick Panel fly distance approx 60',	P(005)	Worker 2, ladder ,crane	610	700
3b*	Place Expansion bolt **See previous P(004)			625	715
3c*	Caulk panel face **See previous P(004)			625	640
4	Control Point Point of control point= Panel Pick/Fly Time End , W2 catches panel	P(005)	Worker2,crane	700	700
5	Set panel W2 open end straddle , W3 (extr.) butt end, W5 (intr.) butt	P(005), Pucks	Workers 2,3,5,crane 700	845	
6	Placement check W1,2 (extr.) check length P(004) to P(005) open, W3, 5 idle	P(005), Pucks	Worker 2,1, tape,crane	925	935
7	Placement check Interior vertical level check P(005) and P(004) correction for plumb ,W2, 3,5 idle	P(005), Pucks	W1,level,crane	950	1000
8	Panel adjustment W1,level,W2(extr.) with bar at open end, W3,5 idle	P(005), Pucks	W1,level, W2,bar,crane	1000	1030
9	Panel adjustment W1(extr.) on ladder pulling butt-end plumb to P(004), W2(extr.) bars wood 2x4 brace for alignment, W3,5 idle.	P(005), Pucks	W1,2 ladder, 2x4 brace,bar,crane	1105	1140
10	Panel adjustment W1 on ladder places strap on pick point and exterior face P(004) butt end, W2,3,5 idle	P(005) ,Pucks	W1,ladder, come-along, crane	1400	1440
11	Drill top hole W1 on ladder, (P005) has 3 precast bolt access in interior face, P(004) solid slab interior and exterior face	P(005) Pucks	W1,Drill,Ladder,c-along,crane	1530	1640
12	Place Expansion bolt (#10) Worker 1 hammers and ratchets from ladder, W2,3,5 idle	bolt1,P(005+4),Pucks	W1,ldr,hammer,ratchet,c-along,crane	1630	1725
13	Remove come along strap W1 on ladder removes strap , W2,3,5 idle	bolt1,P(005+4),Pucks	W1,ladder,crane,c-along	1735	1740
14	Release first lift strap W1(intr) on ladder, W2,3,5 idle	bolt1,P(005+4),Pucks	Worker 1, ladder,crane	1745	1750
15	Release second lift strap W1(intr) on ladder, W2,3,5 idle	bolt1,P(005+4),Pucks	Worker 1, ladder,crane	1750	1755
16	Panel adjustment W3(intr.) with bar under butt end pushing to exterior for plumb, W1 with level open end, W2,5 idle	bolt1,P(005+4),Pucks	W3, bar,W1 level	1830	1900
17a	Drill hole for middle bolt W3 with drill,W1,2,5 idle	bolt1,P(005+4),Pucks	W3, drill,	1915	2005
17b*	Placement of first lift hook P(006) W4 attaches lift strap to P(006), one pick point only	P(006), truck	W4, Crane, ladder	1940	1955
18a	Caulk panel face Worker 1 caulks open end of P(005)	P(005)	W1, caulk	2000	2030
18b*	Panel (006) pick Panel fly distance approx 60',(Time end = point of control point= worker 2,3	P(006) truck	Crane	2005	2100
18c	Place Expansion bolt (#16) Worker 3 hammers and ratchets,	bolt2+1,P(005+4),Pu	W3, hammer,ratchet	2015	2105
18d*	Guide panel to pad W5 straddle open end, W3(intr.) at butt end	P(006),	W3,5, Crane	2100	2125
18e	Drill hole for bottom bolt W3 with drill, W1,2,5 idle	bolt2+1,P(005+4),Pu	W3, drill,	2115	2155
19	Place Expansion bolt (#18) Worker 3 hammers and ratchets,	bolt3+2+1,P(005+4),Pu	W3, hammer,ratchet	2205	2320

NOTE: **red** relates to previous/next panel activity P(004)
NOTE: sequence subscript indicates overlap task times

Table 1: Written Assembly Format for Panel P(005)

6.4. D: *Case-based Study of Production Assembly Communication*

Case-based Study of Production Assembly Communication

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This paper proposes that construction documentation accompanying common building products provides instruction oriented to the definition of integrated parts rather than communicating the procedural assembly required of labor. To better understand this distinction and its influence upon constructability, the character of production information is examined by case study. Installation documentation from three common building products is critiqued for its ability to convey assembly task information and effect labor's procedural response. This examination continues a current academic interest in the instruction of work protocols and the development of construction communications.

Key Words Construction Communications, Assembly Procedure, Task Instruction, Industrialized Production.

Introduction

In the 1970's Japan began to apply production efficiencies derived from factory methodologies to the construction of housing (Gann, 1996). By the end of the twentieth century, the US construction industry has also begun its pursuit of systematic control over residential production. Both efforts strove to introduce pre-engineered products and practices into the always dynamic construction environment. The impact of 'industrialization' onto residential building brought fresh inquiry to the field of construction science and management - particularly in the areas of project delivery information and production modeling.

Developing alongside construction's shift in residential production was the field of construction computer modeling. Maturing over the same period as Japan's foray into industrialized home production - new theories and approaches in construction computer modeling progressed concurrently (Halpin, 1977; Paulson, 1978; Ioannou, 1989; Skolnick et al 90; Martinez and Ioannou, 1994; Sawhney and AbouRizk 1995; Wakefield and Sears, 1996; Shi, 1999; Zhang et al., 2002).

While this paper does not focus on specific industrializing efforts or modeling strategies, it does recognize a purpose shared by both. Their commonality is an effort to systematically format construction's parts, processes and resources for increased control over onsite productivity. Pertinent to this study are the programming challenges onsite operations present to systems-based implementation. (Halpin and Martinez, 1999; Gibb, 2001; Hook and Stehn, 2008). The translation of pre-engineered / analyzed efficiency is influenced by a comprehension of labor's onsite performance. (Halpin and Rigs, 1992; Shi and AbouRizk,1997; Mehrotra, 2003; Wakefield et al., 2003; Senghore et al., 2004). Construction communications are seen as a key interface between industrialized construction and onsite human performance (O'Brien et al. 2000, 2002; Wakefield et al. 2001). Thus the industrialized efforts of construction make its production communications a focus of study.

Three instructional case studies are presented which review the character of procedure's representation. Their instruction sets graphically sequence part relationships and may also include text-based definitions of the work process. Instructional focus on parts addition verses labor's procedural contribution for assembly is of interest to this work. It is suggested that present gaps in site-relevant production information can be attributed to the still-frame format of most construction's communications and the prototyped nature of building materials designed and pre-manufactured offsite. The included cases highlight how production-grade assembly information currently reveals itself and critiques its dependence upon and facilitation of onsite procedural knowledge.

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Case One - Shower Wall Insert

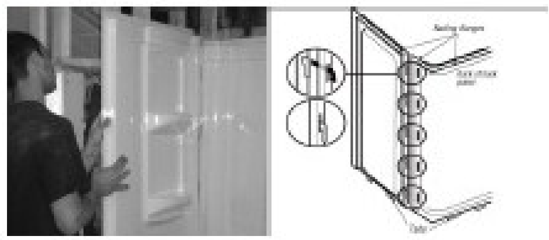

Figure 1: Wall panel insert with diagram

The following case reviews the production information provided with an industry standard residential shower insert. Its informational component includes text-based instructions referencing graphic production diagrams. An example of the text-graphic relationship is observed in the instruction of a panel's connector insertion into receiving slots (see figure 1). The textual instructions read:

- *"Position each end panel so that the hooks of the end panel go into the slots on the back wall and then push down until panel tops are even"*

The use of graphic callouts such as arrows to depict material management is both typical and helpful; however the efficacy of such indicators may be challenged when not uniformly applied. For example, Figure One defines both an assembly process (thick arrow) and material part (thin arrow). The figure's slight variation in iconography adds graphical noise without significantly raising a viewer's capacity to discern their operational difference.

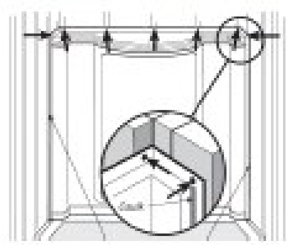

Figure 2: Panel wall attachment diagram

Another example of production information within the instruction set details the shower panel's attachment to the structural wall (see figure 2). The written instructions for the task state:

- *"Locate and drill a 3/16" hole in the center of the nailing flange at the top of the panel and centered on each stud...Hammer 3/4" galvanized roofing nails through each hole and into the studs, securing the wall panel...Add a bead of caulk down the front vertical surface of the back panel"*

Figure two's graphics attempt to indicate distinctly different assembly processes. The drill and nail procedures are combined into one representation of new arrow type - and/or by the graphic inclusion of black 'dots' presumably indicating drilled hole or nail head? One might excluded the latter analysis (i.e., nail head) in the absence of a thin arrow callout previously established in Figure One. Here the part callout (thin arrow) is mismatched to the text's instruction calling for 'addition' process (i.e., caulking). This instance of graphical ambiguity is questioned when iconography specific to the same process is clearly employed in later figures (see Figure 3).

A higher-order discrepancy in procedural communication is found within instructions presented for the plumbing interface. Textual instruction reads:

- *"Decide which side panel will need cutouts for plumbing fixtures. Carefully locate, mark and cut holes using the proper size hole saw"*

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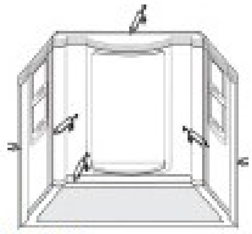

Figure 3: Iconographic depiction of caulking process

No graphic information is provided depicting the tools or processes necessary to affect hole location, marking or cutting (see figure 4). This omission requires that labor provide all suitable work processes for existing conditions. And while it may be common for instruction sets to revert to text-only descriptions when graphical counterparts are unavailable, the inclusion of process-qualifying definitions, such as "Carefully" seem superfluous in the light of the missing representational detail.

Figure 4: Installation procedure for existing conditions

These initial observations while seemingly pedantic offer challenge not only to the fidelity of graphical standards, but to communicative modality – or the clear conveyance of an intended message. If labor is expected to accurately translate vague representation into specific acts of construction, it seems logical that procedural communication could better match onsite production.

Case Two - Roof Shingle Application

This case identifies potential information gaps in the relationship between operational procedure and assembly instruction provided for the standard shingle roofing product (see figure 5). Its instructional format employs a text/graphics combination to convey work's instruction; however a dependency on terminology to define physical tasking becomes immediately apparent.

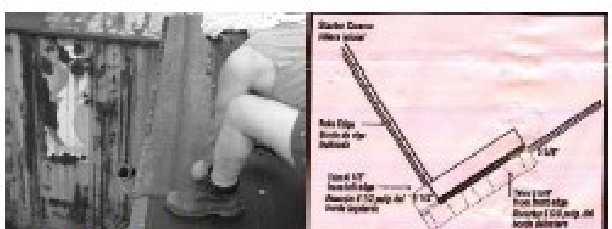

Figure 5: Shingle starter course with instruction

The instruction set's reliance on text is observed for a Starter Course where labor is expected to;

- *"Trim 5 3/8" from the starter course shingle. Trim 6 ½ off the rake of the starter course shingle and flush with the drip edge along the rake and eaves edge, and continue across the roof" (underlines added)*

The highlighted terminology is assumed common to the work domain, yet a participant lacking its conventions is required to inspect the provided graphical figures for clarification. Unfortunately, the diagram corresponding to these terms only indicates two of the five directly - rake and trim (see figure 5). It is noted that two of the other terms are identified in separate figures provided later in the instruction set. Absolute verification of the 'flush'

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process is missing so its definition must be known or deduced. Both graphic and textual 'trim' indications do little to explain that the process of cutting is a once per course event - an omission that could conceivable promote anomalous repetition of procedure.

Setting aside the above-mentioned issues, the information set contains further potential for work's confusion. Procedural ambiguity is identified in the Starter Course text describing the nailing task:

- *"Use 5 fasteners for each shingle, placed 2" to 3" up from the eaves edge"*

The Starter Course diagram never graphically indicates nail parts nor the text's proscribed procedure (see figure 5). The instruction set does provide a separate general conditions diagram indicating a nail configuration which contradicts (e.g. by number and relative position) the Starter Course's instruction (see figure 6). This is a clear example where disparate text and graphical formulations of similar processes may adversely affect worker's comprehension of correct (intended) procedure.

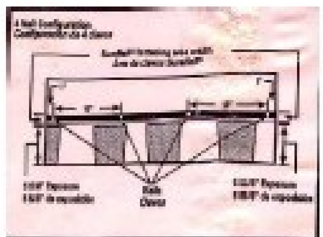

Figure 6: General nailing diagram

A second case of unclear and potentially ambiguous production representation is found with the instructions specifying material distribution. The manufacturer states that roof shingles should be blended through a diagonal roof application to minimize material-bundle color variation. The text indicates this distribution textually by specifying the intended direction of work.

- *"starting at the bottom of the roof and working across and up"*

The only graphics capable of supporting the directive to work diagonally are those indicating the start positions for each new course row. However, all relevant diagrams potentially infer a linear completion of coursework prior to the start of a new rows (see figure 7). The apparent contradiction in text and graphical communication was not speculative in this case — as the operations of inexperienced labor was clearly influenced by the graphical instruction. (see figure 7). Participant review of their anomalous single-axis performance also identified a Starter Course's text directive to, "*...continue across the roof*" (see above citation).

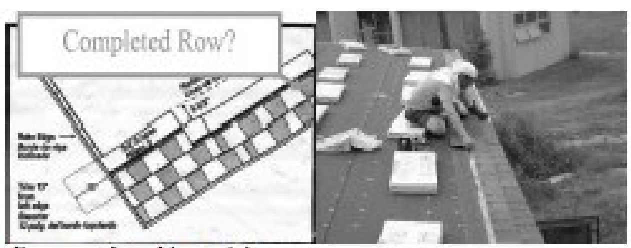

Figure 7: New course diagram and resulting activity

Case Three - Residential Window Installation

The following case reviews the production documentation provided for residential window installation (see figure 8). It was initially theorized that product features such as unit price, warrantee, and market standardization would promote a more developed instructional format in comparison to other cases.

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Figure 8: Window installation and instruction

This case's assembly representation presents a well-integrated yet standard text and graphic combination. Diagrams are sequentially numbered with individual frames attempting to represent a single assembly task (see figure 8). Diagrams indicate a user's point of view in the activity plain and effectively apply 'picture-in-picture' (circled) detailed views of product assembly. Diagrams employ traditional graphic callouts which remain uniform and distinct throughout the entire instruction set. Contrasting previous cases, directional arrows are consistent in their indication of process (i.e. material manipulation), with extension lines limited to the definition of parts referenced by the text.

Concerning the representation of required processes, the instruction set provides limited characterization. Regarding Figure Eight's textual direction to,

- *"center the window in opening"*

Figure 9: Window installation and instruction

-its corresponding diagram lacks any graphical companion. The instruction set does populate diagrams with representations of tooling to suggest work processes (see figure 9). Figure Nine is a good example of tool imagery implying procedure. While the proper tool icons are shown in poses relative to their actual utilization, the figure's compositional approach highlighting multiple activities could cause confusion for inexperience / unskilled labor. Similarly, Figure Nine's accompanying text-based definition calls for procedural checks of;

- *"plumb, level, and square. Diagonals must be within 1/8th inch"*

- without clear indication or positive correlation to the tools providing each activity. Furthermore, it is questioned whether the level's symbolic representation illustrated in Figure Nine has mislabeled the plumb process or is simply identifying the tool itself. The graphical standard established by the instruction set suggests the latter function, and thereby diminishes any attempt to visually supporting the textual call for plumb processes.

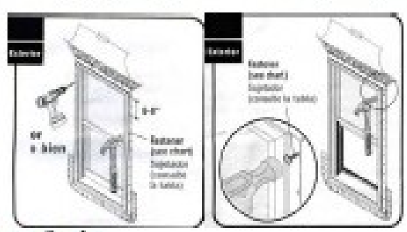

Figure 10: Fasten-all-sides vs. one-nail-only

Overall, correlation between text and graphical task descriptors found within this instruction set is deemed to be higher than for the previous two cases, yet the potential for procedural confusion remains. Consider for example Figure Ten's text-only request to:

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- *"fasten on all sides (of the exterior window nail flange)"*

Its accompanying figure offers little more information than an earlier diagram instructing that one fastener be added to assist initial installation and shimming procedures (see figure 10). While labor might infer a complete nailing process from the secondary tool-icon presented in Figure Ten, its graphic inclusion more likely references the option for alternative mechanical attachments (i.e. screw or nail). In either case, clear graphical distinction between a full or partial fastening procedure is lacking.

Results

Considering the examined cases, it is apparent the production documentation contains communicative elements that can be detrimental to effective procedural instruction. When closely inspected both the literal and figurative elements of instruction sets show weakness in the areas of graphic representation, text-graphic correlation, and descriptive semantics. And while individual anomalies may remain insignificant to overall production, their combinatory effect can challenge the point of instructional communications. The provided evidence builds on a theory that as communication modality decreases instructions may simply be ignored until intuition or training fail into error or uncertainty. What is clear from this cursory review of production information sets is that constructors provide a large amount of practical skill and expert knowledge when translating assembly instruction. And in those instances where instructional modality and labor's task familiarity do not correspond or possibly conflict – the potential for anomalous production exists and may be encouraged.

The examples provided within this study, begin to identify some basic considerations in the design of a more effective procedure-formatted construction communications. A few of these points are summarized as follows:

- When combinatory work processes, resource, or material movements are required, it may be advantageous to define their individual representation in separate instructional frames.
- Graphic representation of tooling can/should reflect intended use.
- Text-based definitions of processes, parts and resources should be supported by graphics that are easily identifiable to the broadest audience.
- The graphic standards chosen to highlight procedural communication should be uniform and discriminating

Conclusions

The instruction sets of three construction products show a common focus in their representation of tooling, materials and aggregate parts. Their approach to procedural instruction identifies common weaknesses in the text and graphic relationship defining tasking. In those cases where text and graphics are not complimentary, labor is forced to reconcile ambiguity. Where communication modality is diminished, the potential for production error exists and may be increased. A common bias is found in part detailing used as a surrogate for clearly defined work processes. The cases also present instructive techniques that imply procedure yet fail to actually define the physical acts and logical contributions provided by onsite labor.

As construction continues to push the boundaries of industrialized production the recognition and integration of labor's onsite processes becomes an increasingly important management issue. The issues highlighted within this paper suggest potential areas for modification of the product-centered and top-down production information traditionally provided by construction's designers to the field. The study agues that construction information accompanying systems-based building products could be better represented by incorporating the character of procedural contributions made by onsite labor. It is theorized that instructions reflecting the operational nature of field-processes will best support industry goals of productivity, safety, and quality.

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