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

[1] PhD Candidate, Myers-Lawson School of Building Construction, Virginia Tech., Blacksburg, Virginia. USA., brjohnst@vt.edu

[2] Director, Myers-Lawson School of Building Construction, Virginia Tech., Blacksburg, Virginia. USA., yvan@vt.edu

[3] Head, School of Property, Construction and Project Management., RMIT University, Melbourne Victoria. Australia., ron.wakefield@rmit.edu.au

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).

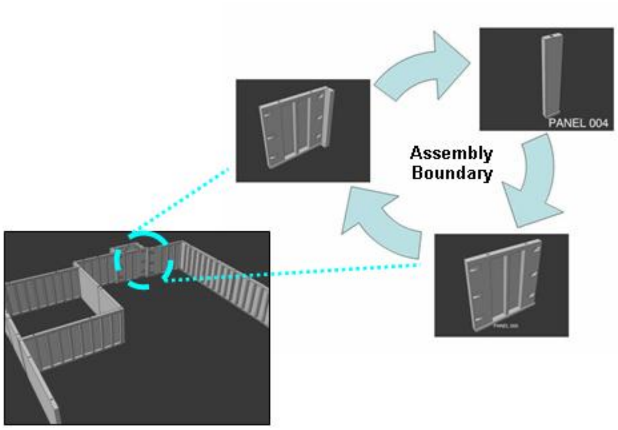

Figure 2: PWS Assembly Boundary

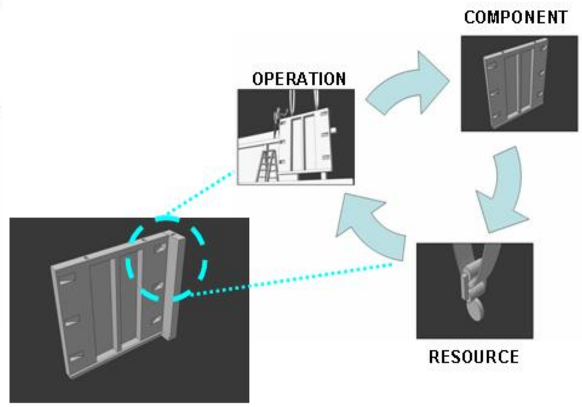

Figure 3: DPM Boundary Characterization

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.

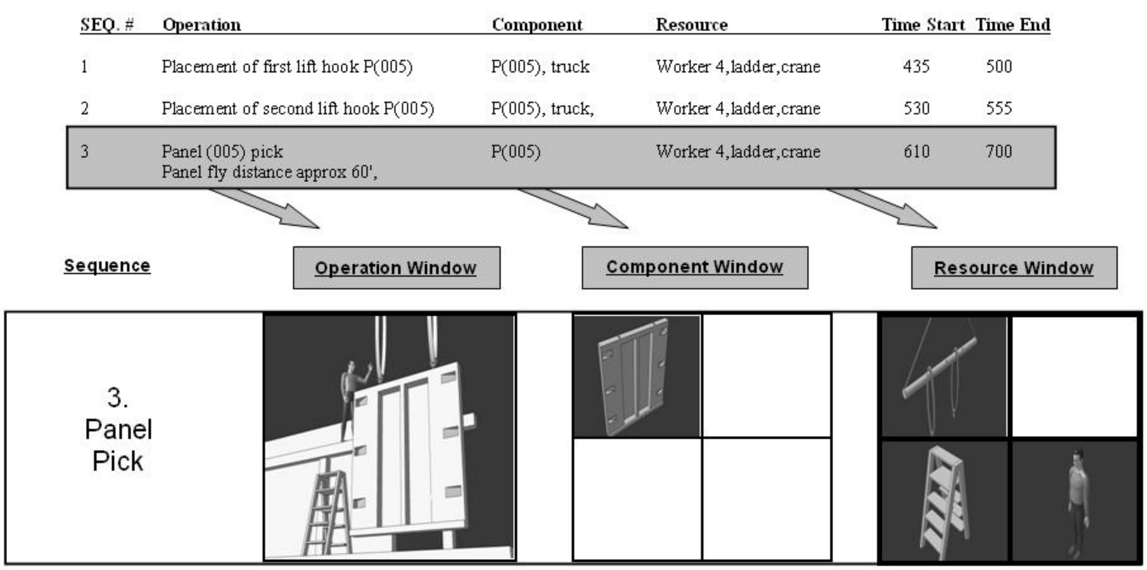

Figure 4: DPM Influenced Task Activity Frame

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.

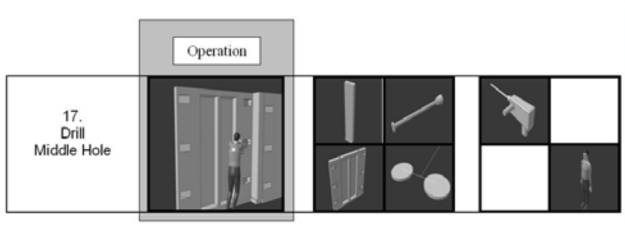

Figure 5: Operations Window

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).

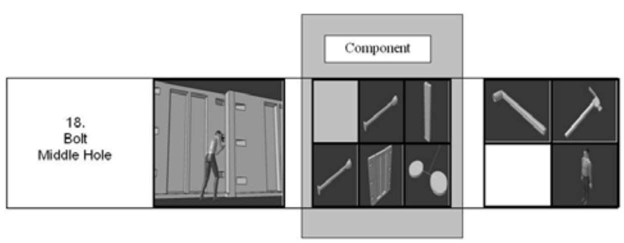

Figure 6: Component Window

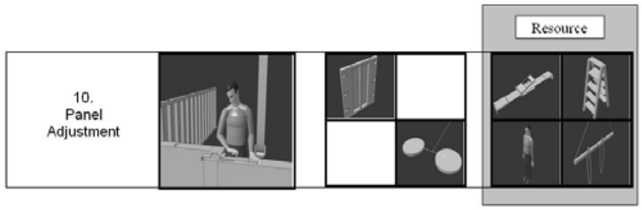

Figure 7: Resource Window

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

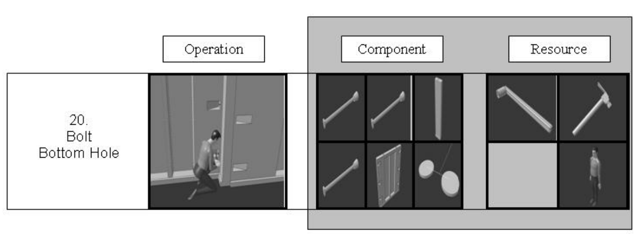

Figure 8: Composite Window Matrixing

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).

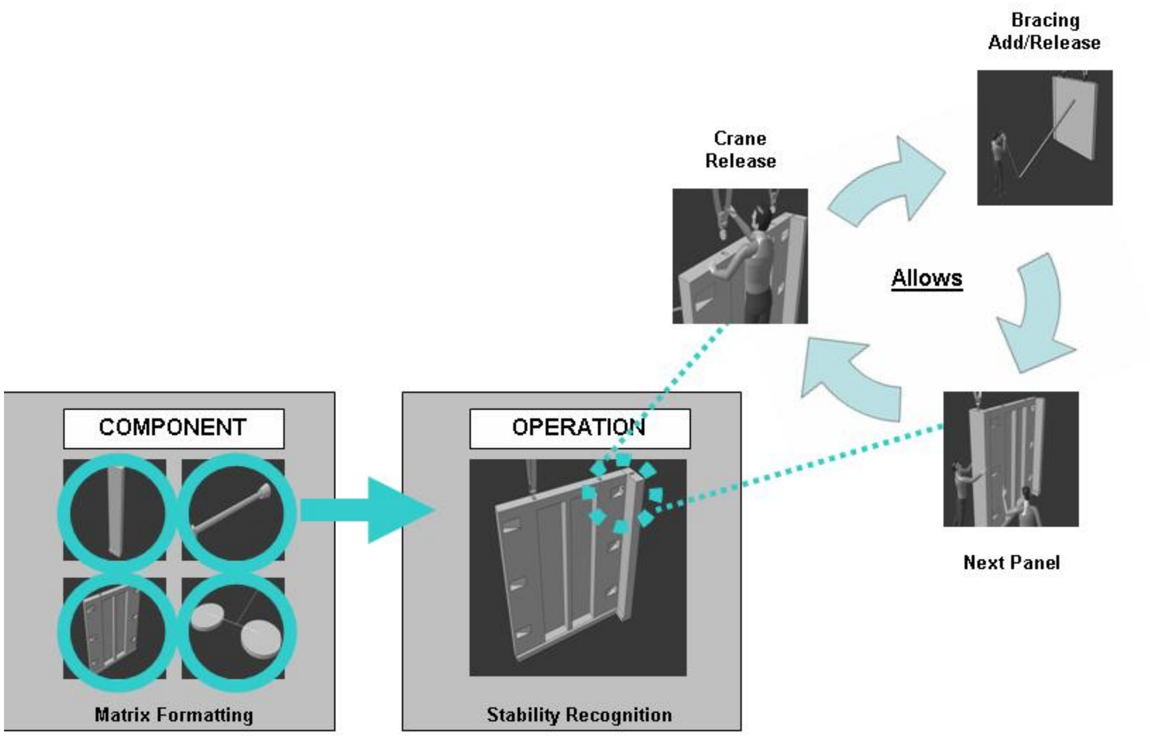

Figure 9: Iconic Production State Recognition

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.

REFERENCES

Albastro, M.S., Beckman, G., Gifford, G., Massey, A. P., and Wallace, W.A. ”The Use of Visual Modeling in Design and Manufacturing Process for Advanced Composite Structures.” Transactions on Engineering Management., IEEE., 42(3), 233-242.

Chang, D. (1987).*RESQUE*, PhD. Diss., University of Michigan, Ann Arbor, Mich.

Gann, D. (1996). Construction as a Manufacturing Process: Similarities and Differences between industrialized Housing and Car Production in Japan., Science Policy Research Institute, University of Sussex, Brighton.

Halpin, D. W. (1977). CYCLONE – A Method for Modeling Job Site Processes. Journal of Construction Div., ASCE, 103(3), 489-499.

Halpin, D.W., and Martinez, L.H. (1999) Real World Applications of Construction Process Simulation., Proceedings., 1999 Winter Simulation Conference., IEEE, Piscataway, N.J., 956-962

Halpin. D. W., and Riggs, L.S. (1992). *Planning and Analysis of Construction Operations*. Wiley, New York.

Huang, R., Grigoriadis, A. M., and Halpin, D. W. (1994). Simulation of Cable-stayed Bridges using DISCO. Proceedings., 1994 Winter Simulation Conference., IEEE, Piscataway, N.J., 1130-1136

Ioannou, P. G. (1989). *UM_CYCLONE User's Guide*. Dept. of Civ. Engr., University of Michigan, Ann Arbor Mich.

Johnston, B., Wakefeild, R.R., O'Brien, M. (2004). Exploring a Virtual Modeling Hierarchy for Construction: Two Case Studies. Proceedings., 2004 Conference on Construction Applications of Virtual Reality., ADETTI/ISCTE, Lisbon, Portugal.

Kibira, D., and Mclean, C. (2002). Virtual Reality Simulation of a Mechanical Assembly Production Line, Proceedings., 2002 Winter Simulation Conference., IEEE, Piscataway, N.J.,

Martinez, J.C. (1996). *EZSTROBE- Introductory General-purpose Simulation System Based on Activity Cycle Diagrams*. EZSTROBE Software Tutorial. Civil and Environmental Engineering Department, Virginia Tech, Blacksburg, Va.

Martinez, J., and Ioannou, (1994). P.G. General Purpose Simulation with STROBOSCOPE. Proceedings., 1994 Winter Simulation Conference., IEEE, Piscataway, N.J., 1159-1166.

McCahill, D.F., and Bernold, L.E. (1993).Resource-oriented Modeling and Simulation in Construction. Journal of Construction Engineering and Management., ASCE, 119(3), 590-606.

Mehrotra, N., Syal, M., and Senghore, O. (2002). *Manufactured Housing Trends and Regulations in Michigan*, vol. 1. Project Report, Michigan State University, Construction Management Program, East Lansing, Mich.

O'Brien, M., Wakefield, R., and Beliveau, Y. (2002). *Industrializing the Residential Construction Site, Phase III: Production Systems*, U.S. Department of Housing and Urban Planning. , Washington D.C.

O'Brien, M., Wakefield, R., and Beliveau, Y. (2000). *Industrializing the Residential Construction Site, U.S. Department of Housing and Urban Planning*. , Washington D.C.

Paulson, B.C., Jr. (1978). Interactive graphics for simulating construction operations Journal of Construction Div., ASCE, 104(1), 69-76.

Sawhney, A., and AbouRizk, S. M. (1995). Simulation Based Planning Method for Construction Projects. Journal of Construction Engineering and Management., ASCE, 121(3), 297-303.

Senghore, O., Hastak, M., Abdelhamid, T.S., AbuHammad, A., Syal, M.G, (2004) Production Process for Manufactured Housing, Journal of Construction and Engineering Management., ASCE, 130(5), 708-718.

Shi, J.J,. (1999) Activity-based Construction Modeling and Simulation Method. Journal of Construction Engineering and Management., ASCE, 125(5), 354-360.

Shi, J., and AbouRizk, S.M. (1997). Resource-based Modeling for Construction Simulation. Journal of Construction Engineering and Management., ASCE, 123(1), 26-33

Wakefield, R., O'Brien, M., and Beliveau, Y. (2001). *Industrializing the Residential Construction Site, Phase II: Production Systems*, U.S. Department of Housing and Urban Planning. , Washington D.C.

Wakefield, R., O'Brien, M., and Beliveau, Y. (2003). *Industrializing the Residential Construction Site, Phase IV: Production Simulation*, U.S. Department of Housing and Urban Planning. , Washington D.C.

Wakefield, R.R. (1998) Application of Extended Stochastic Petri Nets to Simulation and Modeling of Construction Systems. Civil Engineering and Environmental Systems, 15(1), 1-22.

West, A.A., Rahimifard, S., Harrison, R., and Williams, D.J. (2000). The Development of a Visual Interactive Simulation of Packaging Flow Lines, International Journal of Production Research., 38(18), 4714-4741.

Zhang, H., Shi, J.J., and Tam, C.M. (2002). Iconic Animation for Activity-based Construction Simulation. Journal of Computing in Civil Engineering, ASCE, 16(3), 157-164.

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

APPENDIX

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

Panel lift (005)

SEQ. #	Operation	Component	Resource	Time Start	Time End
1	placement of first lift hook P(005)	P(005),truck	Worker 4, ladder,crane	435	500
2a	placement of second lift hook P(005)	P(005),truck,	Worker 4, ladder,crane	530	555
2b*	Drill hole for middle flange bolt			515	550
	**See previous P(004)				
2c*	Place Expansion bolt			515	610
	***See previous P(004)				
3a	Panel(005) pick	P(005)	Worker 2, ladder ,crane	610	700
	Panel fly distance approx 60',				
3b*	Place Expansion bolt			625	715
	**See previous P(004)				
3c*	Caulk panel face			625	640
	**See previous P(004)				
4	Control Point	P(005)	Worker2,crane	700	700
	Point of control point= Panel Pick/Fly Time End , W 2 catches panel				
5	Set panel	P(005), Pucks	Workers 2,3,5,crane	700	845
	W2 open end straddle, W3 (extr.) butt end, W5 (intr.) butt				
6	Placement check	P(005), Pucks	Worker 2,1, tape,crane	925	935
	W1,2 (extr.) check length P(004) to P(005)open, W3, 5 idle				
7	Placement check	P(005), Pucks	W1,level,crane	950	1000
	Interior verticle level check P(005) and P(004) connection for plumb ,W2,3,5 idle				
8	Panel adjustment	P(005), Pucks	W1,level, W2,bar,crane	1000	1030
	W1,level,W2(intr.) with bar at open end, W3,5 idle				
9	Panel adjustment	P(005), Pucks	W1,2 ladder, 2x4brace,bar,crane	1105	1140
	W1(intr.) on ladder pulling butt-end plumb to P(004), W2(extr.) bars wood 2x4 brace in embankment, W5 idle.				
10	Panel adjustment	P(005) ,Pucks	W1,ladder, come-along, crane	1400	1440
	W1 on ladder places strap on pick point and exterior face P(004) butt end, W2,3,5 idle				
11	Drill top hole	P(005) Pucks	W1,Drill,Ladder,c-along,crane	1550	1640
	W1 on ladder, (P005) has 3 precast bolt access in interior face, P(004) solid slab interior and exterior face				
12	Place Expansion bolt (#10)	bolt1,P(005+4),Pucks	W1,ldr,hmr,ratchet,c-along,crane	1650	1725
	Worker 1 hammers and ratchets from ladder, W2,3,5 idle				
13	Remove come along strap	bolt1,P(005+4),Pucks	W1,ladder,crane,c-along	1735	1740
	W1 on ladder removes strap , W2,3,5 idle				
14	Release first lift strap	bolt1,P(005+4),Pucks	Worker 1, ladder,crane	1745	1750
	W1(intr) on ladder, W2,3,5 idle				
15	Release second lift strap	bolt1,P(005+4),Pucks	Worker 1, ladder,crane	1750	1755
	W1(intr) on ladder, W2,3,5 idle				
16	Panel adjustment	bolt1,P(005+4),Pucks	W3, bar,W1 level	1850	1900
	W3(intr.) with bar under butt end pushing to exterior for plumb, W1 with level open end, W,2,5 idle				
17a	Drill hole for middle bolt	bolt1,P(005+4),Pucks	W3, drill,	1915	2005
	W3 with drill,W1,2,5idle				
17b*	Placement of first lift hook P(006)	P(006), truck	W4, Crane, ladder	1940	1955
	W4 attaches lift strap to P(006) , one pick point only				
18a	Caulk panel face	P(005)	W1, caulk	2000	2020
	Worker 1 cualks open end of P(005)				
18b*	Panel(006) pick	P(006) ,truck	Crane	2005	2100
	Panel fly distance approx 60', (Time end = point of control point= worker 2,3				
18c	Place Expansion bolt (#16)	bolt2+1,P(005+4),Pk	W3,hammer,ratchet	2015	2105
	Worker 3 hammers and ratchets,				
18d*	Guide panel to pad	P(006),	W2,5, Crane	2100	2125
	W5 straddle open end, W2 (intr.) at but end				
18e	Drill hole for bottom bolt	bolt2+1,P(005+4),Pk	W3, drill,	2115	2155
	W3 with drill, W1,2,5 Idle				
19	Place Expansion bolt (#18)	blt3+2+1,P(005+4),Pk	W3, hammer, ratchet	2205	2320
	Worker 3 hammers and ratchets,				

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)