Visualization of Work Flow to Support Lean Construction

R. Sacks[1]; M. Treckmann[2]; and O. Rozenfeld, Ph.D.[3]

Abstract: Implementation of advanced production management techniques, such as lean construction concepts like filtering of work packages to stabilize work flows, pull flow of teams and materials, and in-process quality control, demands effective and timely flows of information both to and from the workface. The key requirement—making the process state transparent to all participants—is more difficult to achieve in construction than in manufacturing, because work crews move continuously within a physical environment that is itself changing. Novel computer-aided visualization tools can fulfill the needs that simpler tools, such as Kanban cards, fulfill in manufacturing. Two prototypes with user interfaces designed to facilitate process flow have been devised and implemented within the context of building information modeling (BIM) software systems. They demonstrate aspects of the synergy between BIM and lean construction. Given the dynamic and dispersed physical environments and the fractured contracting arrangements typical of construction, BIM-based visualization interfaces are important tools for providing process transparency.

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Introduction

Lean construction thinking applied to production systems on site has increased awareness of the benefits of stable work, of pull flow of teams and materials to reduce inventories of work in progress, and of process transparency to all involved. In lean production approaches to manufacturing, optimal process flow is achieved by incremental improvements aimed at reducing variability and by instituting pull flow mechanisms. The Toyota Production System is the archetype of this strategy (Liker 2003). Pull flow is a method of controlling product flow through a series of processing steps in which the quantity of work in progress inventory (WIP) between process stages is minimized, and only products demanded ("pulled") by the ultimate "client" process are produced. The term "lean" itself stems in part from the notion that production systems in which pull flow is used do not have large amounts of WIP. High WIP levels are common in systems with central "push" production control, with large batch sizes and long lead times (Hopp and Spearman 1996). In lean manufacturing plants, pull flow is controlled using a system of signals from downstream to upstream stations to produce something. "Kanban cards" are the classic form of the signals that make the process transparent to all.

However, the physical environments and the contracting relationships typical of construction projects make direct application of the lean techniques that function successfully in manufacturing inappropriate. A key problem is that it is very difficult to visualize the flow of the work in progress on a construction site. This is more obvious for the interior finishing works that comprise the majority of the value in most buildings, but in terms of production flow, it is also true for structural work: the amount of buffered WIP accumulated between work teams cannot be seen by the naked eye in the same way that piles of products that constitute WIP can be seen accumulating between processing stations in a manufacturing plant (Hopp and Spearman 1996).

Achieving smooth and stable flow in production processes is a central tenet of lean thinking (Womack and Jones 2003). The idea is an explicit feature of Koskela's "transformation-flow-value" (TFV) conceptualization of production in construction (Koskela 1992). The TFV approach extends common perceptions of construction as a set of disjointed *transformation* activities, in which materials are transformed to products, to encompass consideration of the *flow* of workers, materials, information, space, cash. etc. through a process. *Value* is the third view of production in construction, enabling identification of waste within any process by distinguishing between activities that do or do not add value for the end customer.

While lean construction encompasses the full life cycle of construction projects, covering project definition, design, supply chains, assembly and use (Ballard 2008), we focus here on the fabrication, logistics, and installation of a building on site. In this phase of construction, forming a coherent view of a project's flow status requires integrating and interpreting monitoring data gathered from various sources (Navon and Sacks 2007). Computer-aided visualization, not only of the construction product, but also of the construction process, can facilitate reporting of project status. More important, however, it can provide a unique service to support decision making to achieve stable flows and to communicate pull flow signals.

[1]Associate Professor, Faculty of Civil and Environmental Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel (corresponding author). E-mail: cvsacks@techunix.technion.ac.il

[2]Ph.D. Student, Faculty of Civil and Environmental Engineering, Ruhr-Univ. Bochum, Bochum, Germany. E-mail: malte.treckmann@ruhr-uni-bochum.de

[3]Deputy Chief Engineer, Plaza Centers, Budapest, Hungary; formerly, Ph.D. Candidate, Faculty of Civil and Environmental Engineering, Technion—Israel Institute of Technology, Haifa 32000. E-mail: ophir@plazacenters.com

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Table 1. Lean Construction Needs That Can Be Supported by Computer-Aided Visualization Tools

Lean construction requirement	Computer-aided visualization tools
Production system design and production planning	
Plan for stable work—plan project activities effectively, predicting problems and safety issues	4D CAD modeling including space resources and temporary facilities (Akinci et al. 2002; McKinney and Fischer 1998; Retik and Shapira 1999)
Communicate standardized processes to workers	Modeling of production details using BIM and 4D CAD animation videos
Production management and control	
Monitor production and record performance benchmarks for improvement experiments	Visual tools for input of production data
Make process transparent to all	Electronic status boards can show current status of tasks. Progress can also be displayed by superimposing 4D color coded images on site photographs (Fard and Pena-Mora 2007)
Filter work packages for maturity to ensure stability	The last planner system (Ballard 2000) can be supported by visual status charts that show the readiness of equipment, materials, space, information, etc. BIM can support dynamic safety conscious work filtering using the CHASTE model (Sacks et al. 2009)
Pull technical information for work packages when needed	On-line pull of up to date drawings and other information from a BIM server (Sacks and Derin 2006)
Provide pull flow signals to regulate work flow	Work in progress is not visible, like in manufacturing, so directives to action pull work. On-line pull flow is needed and must be communicated to teams (Sacks and Goldin 2007)
Pull detailing and fabrication/assembly of building system components according to short-term planning to match production flow	Collaborative detailing with integration across disciplines (Khanzode et al. 2005)
Just-in-time delivery of materials and parts	BIM can provide accurate and automated preparation of bills of materials for JIT delivery [Chau et al. 2004; Strategic Project Solutions (SPS) 2007]
	Color-coded interface for giving pull signals
Pull management attention to where it is needed, to release bottlenecks or facilitate flow	Visual production flow monitors and safety risk levels can be used to attract management attention to nodes of instability or danger, e.g., use of Andon lights (Pereira 1998) and the CHASTE model (Sacks et al. 2009)
Respond flexibly to change	Design or process changes can be disruptive. Visual planning interface can enable managers to adapt construction plans/material and resource orders/work assignments flexibly and responsibly

Three-dimensional (3D) parametric modeling of buildings has been developed incrementally over three decades. It has evolved into building information modeling (BIM) (Eastman et al. 2008), and can support a wide range of visualizations. Much work has also been devoted to systems for concurrent engineering and design collaboration (e.g., Aspin 2007). The four-dimensional (4D) computer-aided design (CAD) concept (McKinney and Fischer 1998), in which 3D building models are "animated" by linking them to construction schedules that provide the fourth dimension, has been adopted in industry and commercial applications are available for 4D construction planning, such as ConstructSim (ConstructSim 2009) and Synchro (Synchro 2007). Akinci et al. (2002) demonstrated how work spaces and temporary facilities could be generated and added to 3D building design models to enable evaluation of construction plans for space conflicts. Retik and Shapira (1999) proposed virtual reality manipulation of construction equipment to evaluate the practicality of construction plans. Some systems incorporate cost as a "fifth dimension" of project information and aim to enable "virtual construction" (VICO 2007). Among the small scope of visualization research that deals with day to day operations onsite are applications of virtual reality (Fard and Pena-Mora 2007), augmented reality (Behzadan and Kamat 2007), and visualization of simulations of construction operations (Kamat and Martinez 2001).

This paper presents two prototypes of software interfaces designed to facilitate process flow that have been devised and implemented within the context of BIM systems. One deals with long- and short-term safety-conscious planning of work packages to ensure stability, and the other provides process visualization and pull flow signals to trade teams for interior finishing works. Although different in application, they are similar in concept—both use visualization based on building information models to implement lean construction methods in a fashion appropriate to their contexts.

Construction Visualization Support for Lean Construction

When considered in the broad systematic perspective of construction planning and production control that lean construction thinking provides, it can be seen that 4D CAD applications address some of the lean needs in terms of production planning and production system design, but require further development to aid in production management and control. Table 1 presents a set of lean construction management requirements for both planning and control. The right-hand column of the table provides examples of the ways in which computer-aided visualization can support each requirement. The list of lean requirements is distilled from the extensive literature on the subject, but is not comprehensive, including only those aspects of work flow on site that are relevant for support by computer-aided visualization.

The first requirement listed in Table 1, planning for stable work, primarily means ensuring that work can be done in a predictable manner, without interruption and at the required level of quality. Kang et al. (2007), Jongeling et al. (2008), and others

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have shown that 4D CAD helps meet this requirement by communicating the proposed flow of operations effectively to planners, helping them ensure that the requirement for space—one of the seven preconditions identified by Koskela for smooth flow in construction (Koskela 2000)—will be met reliably. When used with a fully detailed fabrication level building information model, 4D CAD animations of specific work sequences are an effective tool for devising and communicating standardized work procedures. The use of a meticulously detailed animation to plan and communicate intent to all participants for a complex time-limited task that involved placing precast beams over an underground railway track in London, as part of the Channel Tunnel Rail Link (CTRL) project (Koerckel and Ballard 2005), is a good example of this application.

The first requirement listed in Table 1 associated with production management and control is the need to monitor production progress. Measurement is essential both for evaluating process status and for benchmarking to test any proposed process improvements. Visual representation of the work to be done in a manner that can be easily identified by workers, using a medium through which they can also report work done, can facilitate monitoring. The "Workmanager" interface presented next partly meets this need.

The following requirement is to make the work process status visible to all. Greif (1991) described the need to create an "information field" accessible to all in order to achieve a visual factory, rather than communication through specific channels. In construction projects status information is complex, diverse, plentiful, and difficult to integrate. Computer-aided visualization of process status is needed because status cannot be easily seen on a construction site due to physical obstacles and because work crews do not have fixed location workstations. Given high degrees of rotation of teams on construction sites, the status should be displayed in a manner that can be readily understood by all, regardless of their technical knowledge (Santos 1999) or the amount of time they have spent at the site. The Fard and Pena-Mora (2007) construction progress reporting technique, in which an image generated from a 4D CAD system (which shows planned progress) is superimposed on a still photograph of a site (which shows actual progress) is a good example of this principle.

Filtering work packages to avoid assigning work that cannot be done as planned is commonly done using the last planner system of production control (Ballard 2000). The Choo et al. (1999) "WorkPlan" system applied a database of work packages and constraints to support the process. Here too, 4D CAD simulation can aid in evaluating whether space requirements will be met. Status visualizations can clearly show information defining the locations of other crews, the state of completion of prior work, and the availability of materials, all of which are preconditions for stable work assignments.

The visual reports produced using the Construction Hazard Assessment with Spatial and Temporal Exposure (CHASTE) method (Sacks et al. 2009), the second interface example described next, help planners evaluate whether their work assignments are sufficiently safe. Construction is one of the most hazardous industries all over the world (ILO 2003). One of the reasons for poor safety performance is the difficulty of identifying exposures to hazards. The dynamic nature of construction sites demands continuous proactive risk assessment. Mapping workers' exposures to risks has needed professional experience and mental visualization of the construction site (Chantawit et al. 2005). A 4D safety risk visualization software application developed by Bechtel (Berg 2005) used color codes to highlight dangerous locations according to activity types. This provided visualization of risks, but the underlying calculation neglected the exposure of workers to risks posed by activities other than their own, such as the significant danger posed by construction equipment like tower cranes.

All of the following five needs listed in Table 1 are concerned with pull flow. This aspect of lean construction is a prime candidate for application of computer-aided visualization because of the difficulties posed by the fact that on construction sites, workers move from location to location and usually cannot clearly see or interpret the production rates or locations of teams ahead of or behind them in the work sequence. The next section of the paper and the descriptions of the interface examples below present and discuss this aspect in depth.

The final item listed is the need to be able to respond flexibly to change. When design changes or other factors outside of the control of the site management force changes to the sequence of construction, managers must respond by changing material and work orders as quickly and flexibly as possible. A visual interface to a BIM model, that supported thorough definition of work packages and their relationships to the construction products, would enable managers to visually select the work packages for immediate execution and have their material requirements measured automatically and compiled for delivery. Such an interface is an appropriate subject for future research.

Finally, most of the visualization techniques discussed rely on the availability of a building information model. Eastman et al. (2008) defined BIM as the "tools, processes, and technologies that are facilitated by digital, machine-readable documentation about a building, its performance, its planning, its construction, and later its operation." BIM extends the basic concept of a 3D or 4D model to incorporate other information about a project, including integration of a construction project's management information (which would normally be maintained in a contractor's management information system).

Process Visualization and Pull Flow Control in Construction

Formoso et al. (2002) defined transparency of a process as the "ability of a production process . . . to communicate with people." From the literature, they compiled a list of benefits of process transparency relevant for construction

- In workplaces where the layout changes frequently, effective location information aids people to identify workstations and pathways.
- Display of information at the workplace improves the effectiveness of production planning and control.
- Visual communication tends to increase the involvement of workers in continuous improvement efforts, since it allows rapid comprehension of and response to problems.
- Control is simplified, reducing the propensity for errors and making them more visible.
- Process transparency has a positive impact on motivation.

Process flow visualization using Kanban has been applied in construction in numerous ways. For example, a Brazilian construction company implemented a physical Kanban card system to enable masonry wall production cells to pull materials to their work floor autonomously, as shown in Fig. 1. The application of SPS software [Strategic Project Solutions (SPS) 2007] to pull supply of concrete to the worksites of the CTRL project in the U.K. is a more sophisticated application of the same technique,

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Fig. 1. Kanban cards used to pull materials to masonry wall teams in a residential building (Edificio Vila do SOL, built by Fibra Construções Ltda./Eugenio Montenegro; Sensei: Eng. Pedro Eduardo Pereira) (Pereira 1998)

with the added benefit of reducing demand variation (Koerckel and Ballard 2005).

While these examples apply to pull of materials, a greater challenge specific to construction is to pull work teams to the right place at the right time. Pull from downstream teams cannot be applied across the full span of a project, because trade teams are not all present at the site throughout project duration (construction extends beyond production per se to erection and dismantling of the production facilities themselves). CONWIP (controlled WIP) (Hopp and Spearman 1996) type systems are appropriate because they can operate independently between consecutive teams. However, the multiple partitions in buildings make it extremely difficult for any work team to see the location, let alone the progress, of other work teams, and the status of some of the conditions for future work, such as the availability of design information, is intangible. Thus effective visualization of the process and its status is a prerequisite to implementing any kind of pull mechanism.

Work Flow Visualization Examples

The following examples illustrate the use of computer-aided visualization tools to achieve process transparency and pull flow in construction. Each has been developed and implemented to different degrees, and they are not the only examples [the DPR construction company's use of a BIM model view to pull detailed design activity for a medical building's MEP systems is another (Khanzode et al. 2005)], but taken as a set, they provide insight into the direction for future highly visual interfaces for this purpose.

User Interfaces for Finishing Trades in Commercial and Residential Construction

Coordinating the flow of interior finishing trade teams to building locations for commercial or high-end residential projects is a complex task because the sequence of maturation of design information for each space usually does not match the physical sequence of spaces in a building's layout (Sacks and Goldin 2007). The challenge is to prevent accumulation of WIP by directing teams to work in locations where the work can be completed in a single uninterrupted sequence. Two parallel research and development efforts by the writers, one for commercial and the other for residential construction, illustrate the need and a potential aid to solving this problem.

The 40,000 m^2 "Galeria Baltycka" mall in Gdansk, Poland, completed in 2007 with 200 shops on three main floors, provided the impetus for research collaboration to develop an electronic

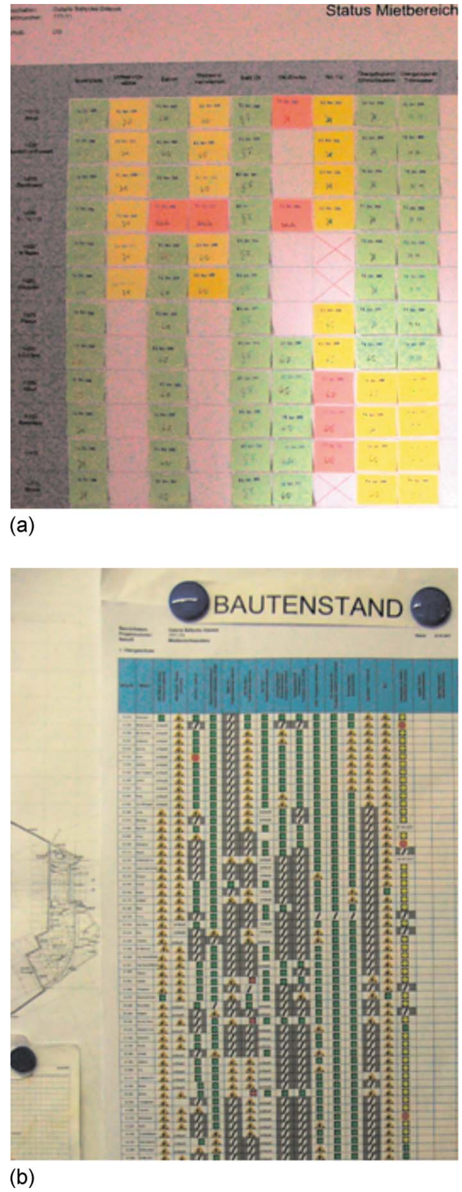

Fig. 2. (a) Paper and sticky note status board; (b) status chart updated and printed daily in Excel

"status board generator." Each shop was quite different in both area and construction work content, and there were frequent design changes. The construction management challenge was to coordinate the multitude of trade teams, equipment and material deliveries, etc. A department comprising eight construction managers was responsible for the coordination of the interior works. A status board was proposed as a means to help visualize the process, first so that it could be coordinated effectively, and second as the first step toward changing the push production control to a pull system. The basic status board concept is a two-dimensional matrix with rows for the process stages and columns for the work locations. The process status is represented using small icons drawn in each cell. The icons indicate not only status but also provide signals for future work.

The first prototype was a printed board [Fig. 2(a)]. Status icons were set by team leaders at the end of each day, and work signals were posted by managers overnight. This provided a "ticket" system, in which each process team essentially provided the green

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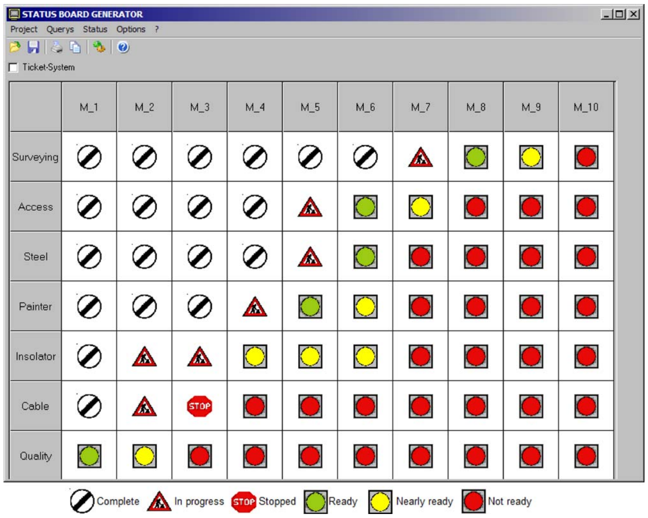

Fig. 3. Status board generator interface, with CONWIP=2

light for the following team to move to the space it vacated. Viewing along rows showed the rate of progress of teams and revealed bottlenecks, viewing down columns showed the status of each space. The status board was then implemented in an MS Excel spreadsheet solution [Fig. 2(b)], which was printed after each update. Numerous icons based on common traffic signals and signs were used and progress indicators could be calculated by computing differences between the daily worksheets that accumulated. However, both of these suffered the intrinsic limitation that they could only be viewed at the site office. They also presented a great deal of information, which made it difficult for any particular trade supervisor to isolate the information relevant to them. Although the status board was a major improvement for the centralized project managers, it was not practical for visualization by the whole work force and could not effectively be used for pull flow. An online method with a straightforward interface was needed.

The status board generator software was the next step. Implemented using MS Access with a VBA user interface, it enabled the work status for any location and trade to be changed simply and provided the same visual icons, as can be seen in Fig. 3. This implementation enabled evaluation of work rates and identification of bottlenecks in flow, but was still not widely accessible.

The traffic signal and sign icons used in the status board generator were based on earlier work in residential construction in which a "pull flow control" chart was proposed for managing the flow of trade teams in high-rise residential apartment construction (Sacks et al. 2005). The pull flow control interface was subsequently implemented by a large construction company within the framework of its WorkManager system, as shown in Fig. 4. The interfaces to the database system were provided to the contractor's supervisors and to trade crew supervisors on rugged tablet PCs, via G3 cellular Internet communication (Sacks and Derin 2006). The main feature that enables the system to implement work flow pulled by design information (i.e., pull by the client at the end, rather than push from the beginning) is that the sequence of apartments introduced for work (shown as #5, #7, #3, #11, and #2 in Fig. 4) can be set to match the information flows.

Fig. 5 is a legend for the icons. The red and amber signals are the primary means for preventing trade teams from accumulating WIP by working in zones where work should not be commenced. The green signal is essentially a Kanban card. The total number of "under construction" and "available" (green signal) icons can be limited to a maximum amount of WIP for the sys-

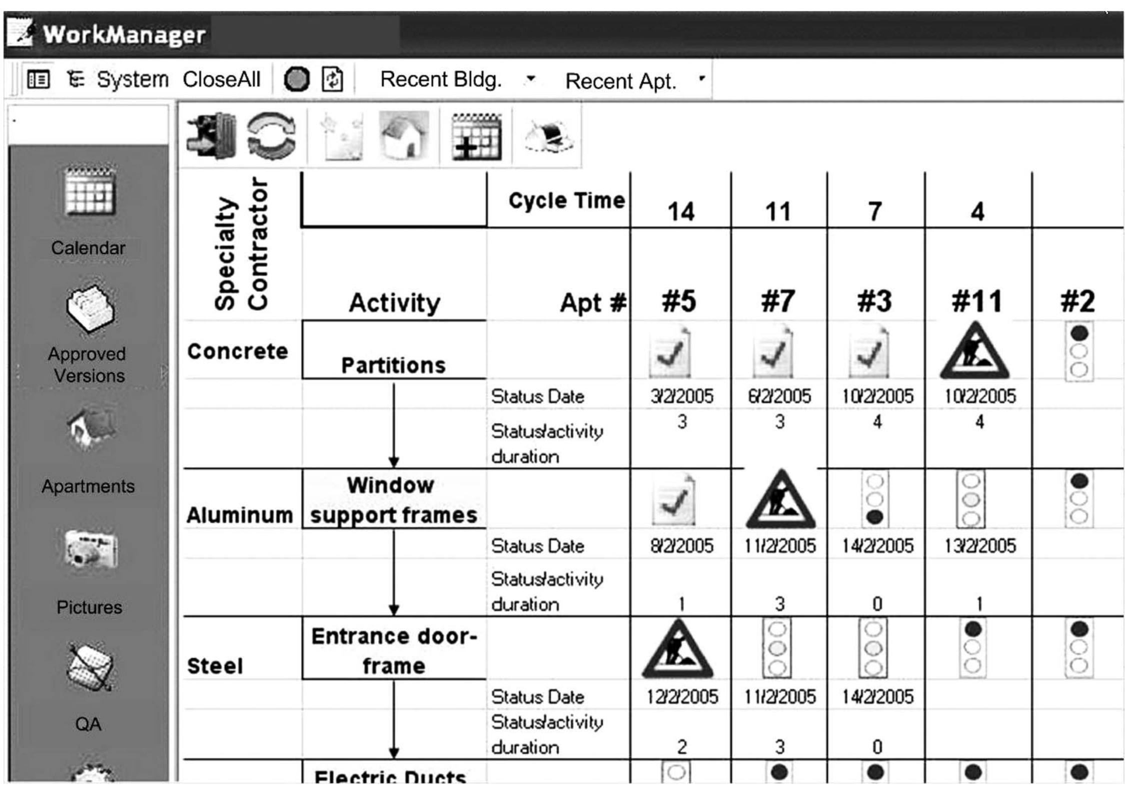

Fig. 4. Electronic pull flow control chart (Sacks and Derin 2006)

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Fig. 5. Work package status signals

tem, the CONWIP level. The system calculates and displays the cycle time for each apartment to date and the duration since the last change for each status icon. Any status duration longer than the TAKT time for under construction or available signals in any row indicates a bottleneck; each green signal is a unit of WIP not being processed. The absence of any under construction icons sign in any column indicates a location in which no work is being done, which also indicates unused WIP. Thus a quick glance not only reveals the location of all work crews, but also shows the pace of work, bottlenecks that need attention and where WIP is accumulating. Since it is delivered on a mobile platform and is accessible to all trade team supervisors, including the ability to set the three signals in the right hand column of Fig. 5, it also enables flow of updated status information directly from the work face to all of the company's information systems.

A status board interface with pull flow sequencing and signaling of this kind is more accessible to workers on site than either Gantt or line-of-balance charts. It enables two way communications about project status and short-term future planning. The amber signals show trade teams where and how much work can be expected in coming days, allowing them to allocate resources with greater predictability of future release of work.

An important drawback at this point is that people viewing the board may not be familiar with the locations of spaces according to their ID alone. Fig. 6 shows a graphic BIM interface, on which work status icons are shown for each location in a 3D model view. This representation significantly enhances readability, providing the status, the duration for which the current status has been valid, and the expected remaining status time where relevant. Each view of a 3D status chart is tailored for a particular trade. A trade supervisor can see at a glance where his/her team should move next, how much work will become available in the near future, where work should not be done, and where rework is required. Reporting of progress is equally intuitive and less error-prone than it is with an alphanumeric interface; trade supervisors can change status from available to under construction to report start of work in a location and from under construction to "complete, awaiting approval" to pull inspection. They can also update the remaining expected work duration for locations under construction.

Safety-Filtering for the Last Planner System

Managing safety at construction sites is one of the most important tasks for project managers. The characteristics of construction sites mentioned earlier, that distinguish them from stable manufacturing settings, also make management of safety difficult (sites undergo physical changes, teams move around the site, etc.). In-

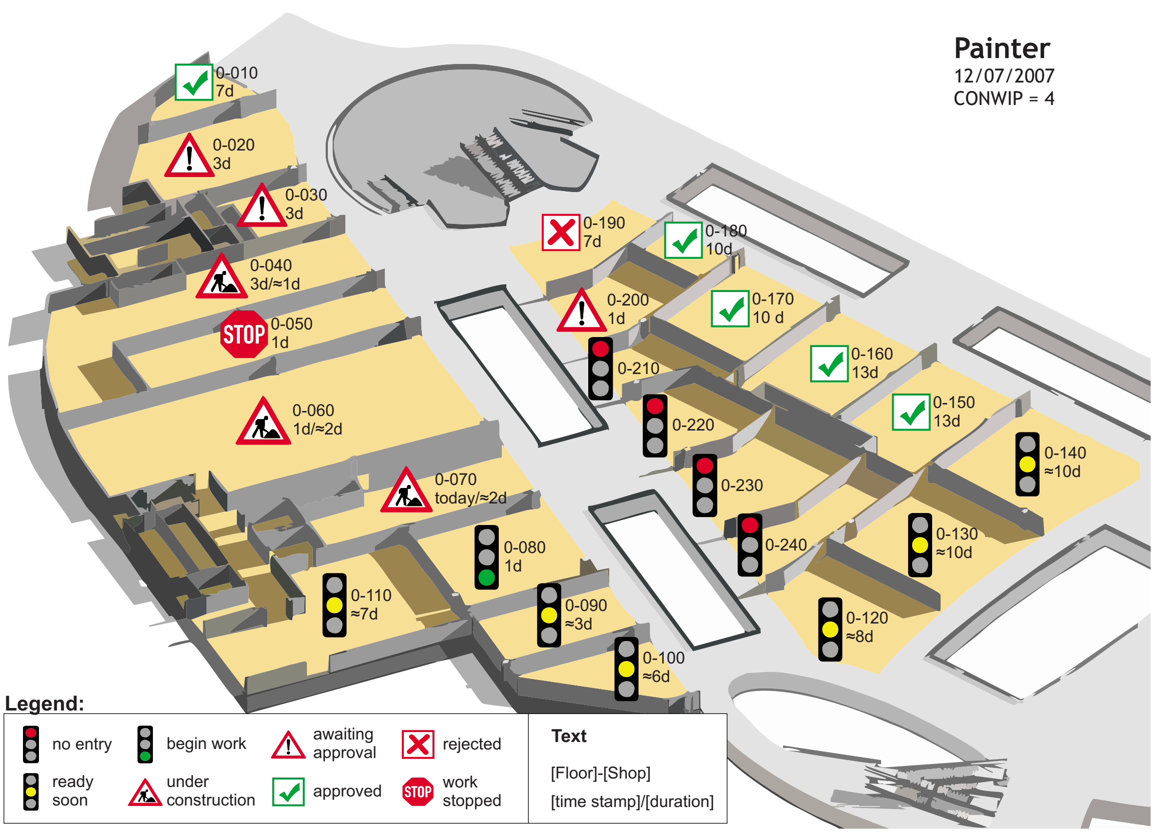

Fig. 6. Proposed 3D visualization of past, present, and future work status for a trade. The total count of under construction plus "begin work" symbols cannot exceed the CONWIP level.

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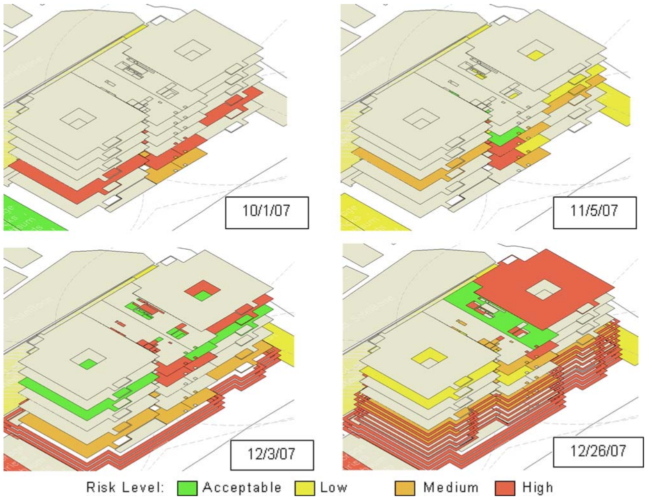

Fig. 7. Four frames of a risk assessment animation prepared for construction of a high-tech laboratory and office building. Each frame illustrates the distribution of risk levels through the building on one day.

tensive hazard analyses at construction sites are rarely performed (Tang et al. 1997). The resulting lack of accurate and timely information describing risks results in inefficient or ineffective safety management. Standard two-dimensional (2D) construction drawings describe the construction product, but not the process; they have little utility for safety management, because managers must form their own mental model of the important information describing the flow of workers and equipment (Chantawit et al. 2005).

Sacks et al. (2009) proposed a model that informs construction planners of safety risk levels for each team at all degrees of planning resolution. The goal was to enable “risk leveling” when planning, filtering tasks for safety risks in last planner assignments and for pulling safety management resources to the times and places that need it most. The model, called CHASTE, integrates project information (construction schedule and a 3D building model) with a detailed knowledge base of a variety of construction methods and their potential loss-of-control scenarios and their probabilities, to compute workers’ exposure to hazards and their associated levels of risk. The hazards may be self-imposed, but they may also be created by other workers at remote locations; for example, while preparing formwork for an exterior concrete wall, a worker may drop an object on a worker installing curtain wall rails three floors below.

A software prototype has been implemented to demonstrate the model’s function and to test the reporting interfaces. Fig. 7 shows four frames of a risk assessment animation prepared for construction of a high-tech laboratory and office building. Each frame illustrates the distribution of risk levels through the building site on one day. The risk level visualization is achieved by coloring the locations in four grades along a scale ranging from green (minimal risk) to red (highest risk). Detailed information about the nature of the risks in any zone can be obtained by selecting the region, as can be seen in Fig. 8. It shows the dialog obtained after selecting the 5th floor hollow-core slab zone, and shows a filtered ranked-order list of the most threatened teams in the zone for a particular day.

The 4D risk level visualization can support users of the Last Planner System. For master planning, risk leveling becomes possible. Running a CHASTE analysis of a proposed master plan

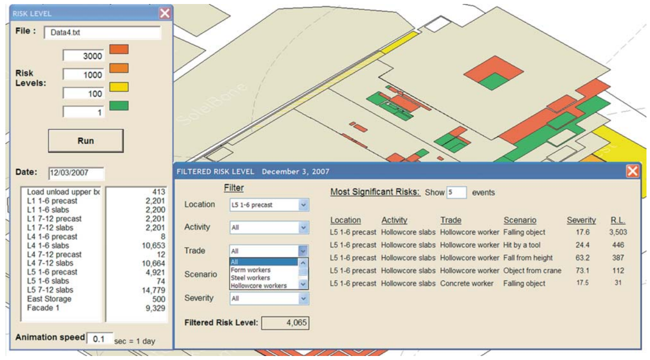

Fig. 8. Pop-up dialog showing a filtered and rank-ordered list of the most serious risks for the zone queried

reveals peaks of risk level; by rescheduling activities that have a critical effect on risk level, or changing activities’ duration or even construction methods, a plan with low risk levels may be developed. For weekly work planning, the model helps identify peak risk levels and avoid assigning particularly risky combinations of tasks. Once task assignments are finalized, a renewed analysis can alert managers and workers to the risks they will face. A future step planned for development of the visualization is to prepare a colored paper drawing for each team for each work period that highlights all risk zones within their planned work area, with annotations describing the risks that can be expected.

Summary and Conclusions

A majority of the research effort in the area of visualization in construction has been devoted to design (3D) and construction planning (4D). Yet the need for visual tools for production management during construction is acute because the physical conditions of construction sites make it very difficult for most participants to form a clear mental image of what is transpiring and what can be expected in the near future. Given the dynamic and dispersed physical environments and the fractured contracting arrangements typical of construction, BIM-based visualization user interfaces are ideal tools for providing process transparency.

The two examples presented demonstrate how building models can be leveraged to generate 3D visualizations of a construction process, helping institute better ways of managing the work itself. Communication of Kanban type pull signals using an online 3D status board display tailored for each trade is a basic enabler for CONWIP type production flow management. Providing visual safety risk forecasts with detailed information in a manner that accounts for short-term schedule changes can contribute to better weekly planning and make each worker more alert to the specific risks he or she faces.

The potential benefits of this kind of user-interface in the day-to-day construction context are numerous. The information delivered is structured, centrally stored and readily accessible. Communication is asynchronous, reducing the dependence of work teams on people in key site management positions. The status board also aids in data collection for progress monitoring, making project status information available to all levels of management. The CHASTE model enables pulling of safety resources such as inspection, equipment and training to the right people at the right time. Both systems increase process transparency: the

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physical and managerial state of the site becomes clearer, potentially increasing workers' motivation and safety perception, thus improving work flow and reducing waste as visualizations help to reduce uncertainties and misconceptions.

While the examples underline the potential, they also raise issues for further research. Practical experiments to measure the expected benefits quantitatively will only be possible once sufficiently robust software is developed to enable reliable use through the life of a project. Live links between the BIM software and construction companies' management information systems are essential, which requires that the correct relationships be established between the systems' object schema. A fully operational CONWIP system will require novel heuristic or other logic to drive its near real-time autonomous decision making about how teams should flow through projects with highly variable design information flows. There are also technical challenges related to the means of delivering the 3D information to work teams on site, and the user interfaces themselves will require research and development.

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