Development of a System to Enhance Residential Construction Ergonomics and Productivity Using Wall Panels

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Abstract

Premanufacturing (or industrialization) is a contemporary trend in residential construction, one important aspect of which is the use of panelized walls (aka panels) that are generated by a designer. While this approach provides increased efficiencies, the centralization of design provides an opportunity to promote ergonomics in the design process and is critical given the physical demands involved in building with panels. There are also opportunities for even greater efficiencies (e.g., reduced safety & health costs, increased productivity) and effectiveness (e.g., fewer incidents and injuries). We have developed a prototype decision support system (DSS) for panelized design and construction. This software system facilitates a more proactive approach to ergonomics in panelized construction, consistent with the philosophy of prevention through design (PtD). A primary advantage in our approach is the inclusion of both ergonomics and productivity as fundamental components that are both improved. As such, it addresses the need to support the economic and/or business case for PtD, specifically by providing information relevant to necessary financial considerations in decision-making and an understanding of the financial implications of PtD. The DSS logic can be expanded to other circumstances within and beyond construction in which a central designer or design process exists.

Keywords

Ergonomics; prevention through design; lean; residential construction

1. Introduction

Compared to the general workforce, occupational injury rates are high in construction, and this sector accounts for ~10% of all non-fatal occupational cases requiring days away from work (BLS, 2009). Roughly 20% of these were attributed to overexertion and repeated motion, and work-related musculoskeletal disorders (WMSDs) overall are more common in the construction industry than in any other sector except for transportation in the U.S. (Weinstein et al., 2007). Occupational injury costs are particularly high in residential construction and among laborers and carpenters. When examined by the nature of injury, muscle strain is identified most frequently among all other mechanisms, and except for minor injuries, the back and shoulders are by far the most frequent sites of injury (Dement and Lipscomb, 1999; Waehrer et al., 2007; Lipscomb et al., 2008a, b). Hence, ergonomics issues are particularly relevant in residential construction.

Controlling WMSDs in construction involves several particular challenges (e.g., Vedder and Carey, 2005; Ringen and Stafford, 1996; Forde and Buchholz, 2004), which as a whole may account for why the construction industry has been somewhat slow to address ergonomics issues. While the industry is complex, it is not unique either in terms of the potential benefits from incorporating industrialization and reducing ergonomic exposures, both of which can be obtained through improved design.

Indeed, Prevention through Design (PtD) – aka Construction Hazards Prevention through Design (CHPtD) and Designing for Construction Safety (DfCS) – has received increasing attention as a means to reduce safety hazards. A primary goal is to encourage designers and architects to consider safety early in the project life cycle (e.g., Behm, 2008; Schulte et al., 2008; Toole and Gambatese, 2008). While roles for contractors and employees later in the life cycle are still acknowledged, PtD is justified by the lost opportunities when interventions are considered only later in the life cycle (e.g., Fadier and De la Garza, 2006). Safety in (construction) design has been promoted and studied in the construction industry by several groups, in which primary attention is given to eliminating hazards through changes in work practices, substitution, or redesign (Gambatese and Hinze, 1999). Our approach (described below) is consistent with this concept, but focuses on ergonomic concerns (i.e., exposures and risks).

Given the potential for design impact in safety (and arguably ergonomics), it is unfortunate that there is not more substantial designer involvement, and several explanations have been identified (Gambatese et al., 1997; Gambatese and Hinze, 1999; Hecker and Gambatese, 2003). Generally, construction designers have limited education and experience related to construction processes and safety, and comparable results have been reported with respect to ergonomics (Kim et al., 2008). One particular barrier is the lack of tools or guidelines (Gambatese et al., 2005). Though such tools exist, most of which address safety hazards related to acute trauma (e.g., falls), they do not include ergonomic issues, however, and none address aspects related to production.

2. Panelized Construction

Our efforts to facilitate ergonomics in residential construction design are focused on the development of a PtD tool to enable designers and other decision-makers to incorporate ergonomics (and production) issues into their design process for one aspect of residential construction. We have focused on construction using panelized walls because of the complexity of the construction process, increasing adoption of panelization, and existence of a central designer. In contrast to traditional stick-built walls, panels arrive at the work site more completely assembled and are typically delivered on pallets containing 15-40 panels stacked 1-3 meters high. A panel designer, working from an architect's drawing, specifies panel sizes and several aspects of preassembly. A carpentry crew then transfers and erects the panels at required locations on site.

Existing evidence suggest that panelized construction reduces construction time, material use, waste, and labor and material costs, and the need for skilled labor (NAHB, 2009; SBCA, 2009; Shepard, 2000). While the panelized approach provides clear savings in many areas, present construction methods may also result in greatly increased risk of worker overload and injury (Kim et al., 2011). Since panels are produced in a factory, production- and transportation-related objectives are typically employed. As a result, panels can be either too large for workers to handle, or too small, resulting in increased material handling. Further, since the current approach involves a separation between design and onsite activities, process efficiency is not as high as it could be otherwise.

3. An Approach to PtD in Panelized Construction

Our approach encompasses panel design and all downstream activities up to and including on-site construction. These activities include determining how panels will be arranged into stacks for delivery to the job site, when stacks are to be shipped, where they are to be placed on arrival, what tasks should be used for each panel, which workers should work on each panel and when. Thus, we have a sequence of related design and planning problems to solve, and implement PtD at each step of the process. Broadly, two approaches are possible: (i) model mathematically and attempt to solve optimally, or (ii) develop approximate solution methods (*heuristics*) and use computer simulation to generate alternative, feasible solutions. Mathematical models explicitly considering the human worker are almost nonexistent, due to the inherent difficulty in predicting human motion and behavior. Additionally, preliminary mathematical modeling efforts have shown that the problems are both too complex for accurate solution and too large for optimal solution in reasonable amounts of time. Thus, we take the second approach involving heuristics and computer simulation.

The problems of designing panels, determining how they are to be erected, and controlling the construction processes are very similar to product design, process planning, and operations planning in the manufacturing industry. The latter have been widely studied, and heuristic solution methods (many incorporating computer simulation) are well established. In product design, for example, design-for-manufacture/assembly (DFM/A) has been used for many years to design products that are easy for workers to fabricate and/or assemble. Typically, a set of DFM/A "rules" (heuristics) are invoked during product design and used to guide the design process. Computer-automated process planning (CAPP) has been available since the mid-1980s to automatically generate process plans in specific manufacturing applications. One method, generative process planning (GPP), utilizes a set of sequential decision rules for generating process plans automatically, based upon the product drawing. In many manufacturing facilities, production is controlled by local decisions based upon rules that have been shown to perform well. One excellent example is the use of dispatching rules, whereby workers select the next job to run at their machine in real-time, based upon pre-specified criteria. Each of the noted manufacturing problems has been successfully addressed using heuristics. In a similar manner, we are developing a set of "design-for-construction" rules (heuristics) for panelized residential construction.

A decision-support system (DSS) is the best choice for the above approach since multiple users will be involved during different PtD activities and users will require the ability to test various alternatives and adjust final solutions. To evaluate a given set of rules for a particular building, the resulting construction process is simulated on a computer. Data obtained from laboratory-based experiments are used to generate predictions of ergonomic risk (e.g., of a low-back disorder) when that construction process is employed. While it is possible to generate such risk predictions directly via computer simulation, such methods do not general reasonable levels of accuracy except under limited conditions. Thus, laboratory-based data is believed to be the best choice for generating estimates of ergonomic risk associated with a given construction process.

In addition to using computer-based simulation to evaluate the construction process, we also use it to generate a three-dimensional simulation animation of the process. This animation can aid construction designers, managers, and others in visualizing how a given structure is to be erected in the field. Such visualization not only improves understanding of the process, but aids in subsequent evaluation and decision-making. Use of simulation animation for this purpose is well established in manufacturing, but has only recently been seen in the construction domain. In construction planning, implementation of PtD will be greatly facilitated through the use of tools that aid the visualization of hazards (Gambatese, 2008).

Overview and Preliminary Results

Overview of the DSS. Given the building plan (blueprint) for a home, we divide the required decision-making into three steps. The first is concerned with establishing the panelization design, i.e., what panels to employ (dimensions, quantity of and location of openings) for a given plan. Next, we establish the stacking plan, which involves how panels are to be arranged into stacks, the stack delivery locations, and the stack delivery sequence. Finally, we generate the construction plan: how panels are sequenced for construction followed by which construction tasks are to be used and which workers perform which tasks.

To establish how good a particular solution (panelization design, stacking plan, and construction plan) is, three measures are employed: 1) some aggregate measure of overall ergonomic risk, 2) the quantity of workers used, and 3) total construction time. The overall objective in design and planning is to minimize one of the three measures, subject to specified constraints on the other two. Thus, ergonomic aspects are considered directly in formulating the panelization design, stacking plan, and construction plan, an approach that should improve worker health, safety, and performance (van der Molen et al., 2005). Previous efforts to develop computer-aided software tools for construction planning have separated ergonomic aspects from construction planning and scheduling. However, our goal is to *address ergonomics in both design and planning*, consistent with the PtD concept and approach.

We assume that a finite set of alternative materials and configurations are available for panelization and that a finite set of generic construction tasks are identified and quantified with respect to ergonomic exposures (e.g., postures, spine loads) and performance (e.g., task time). Furthermore, the generic construction tasks and exposures are used to predict ergonomic risk (e.g., of a low-back disorder) and performance for any particular construction task and panel definition.

We employ heuristic (approximate) solution methods and then *simulate the entire construction process*, from panel stacks arriving at the construction site through completed construction of the panelized building. Such simulation has been shown to be an effective technique to evaluate decision-making on construction sites (Shi, 2003; Gambatese, 2008). Detailed output (ergonomic risks, worker utilization, etc.) is generated from the simulation, and a simulation animation allows the user to “see” the construction process in action and assess, for example, how the workers must work together and how the various construction tasks are performed. Of note, while the construction tasks for each panel and construction schedule are established as part of construction planning, simply providing these items to workers and expecting them to follow them is not the intent. Workers may be unable and/or unwilling to work in this manner or tasks may be short and numerous enough that time is wasted checking the schedule. Additionally, emphasizing adherence to a rigid construction schedule can result in reduced productivity and quality, such that the actual schedule benefits may be barely worth the effort. Our approach is to instead provide workers with a set of construction rules; when followed, the rules result in the desired assignment of construction tasks and construction schedule. (Note that our approach, including the use of construction rules, does not rely on English fluency among workers, but does assume that an accurate translation is available and that the rules are transmitted and employed.) Our approach also has the advantage of allowing workers (and supervisors, contractors, designers, etc.) to react to changes and unplanned contingencies that might quickly invalidate plans made in advance.

In practice, each of the involved parties (panel manufacturer, transport company, contractor) can use the DSS to establish the design rules to use for their associated activity (panelization, stacking, and construction). These design rules can either be completely specified by the users or a small subset can be provided and the DSS will select the rest automatically (to minimize overall ergonomic risk, the quantity of workers needed, or the total construction time). Either way, the results are used as follows. The panelization design and stacking plan are provided to the panel manufacturer and transport company (if an external agent is used), so that panels can be manufactured and delivered accordingly. Construction rules are provided to the job site and communicated to the workers, who then perform their own decision-making during the building process. To check that construction is proceeding according to plan, the construction schedule can also be provided.

Exposure and Risk Assessments. We use relatively high-fidelity lab-based task recreations (mock-ups). By assessing exposures in the lab, detailed measures of exposure can be obtained that would have been quite difficult to gather in the field. Note that *exposures* here refer to contact with risk factors associated with WMSDs (e.g., postures, forces). The lab studies are designed to achieve two goals. First, tasks are reproduced with a reasonable level of detail and accuracy. Only the fundamental tasks identified from field observations are included, as these were identified as the most physically demanding. Alternative methods used by actual workers are included (e.g., horizontal and vertical lifting), with the final set of tasks based on observed frequencies. Second, exposures are measured to facilitate subsequent ergonomic risk assessment. Lab-based measurements provide the necessary input to these tools, but also fairly extensive additional information to anticipate future risk assessment tools. Multiple and diverse ergonomic risk assessment methods are available, where *risk assessment* refers to the qualitative or quantitative value of risk associated with a given task. We have incorporated a set of existing tools in the DSS to achieve three ends, specifically ease of implementation, common use, and relevance to panelized wall erection. These methods are not intended as complete, but rather as broad and representative of both application-oriented and research-based tools.

Preliminary results indicate potential implications for panelized design, and support the need for the DSS (or a similar system-level approach to CHPtD). WMSD risks (specifically for low back injury) were quantified for several fundamental panel tasks (lifting, carrying, erecting, and moving) and using several panel sizes and weights (Kim et al., 2011). Such risks were quite high overall, with the majority of tasks and conditions imposing unacceptable levels of risk. Initial vertical panel placement, size, and weight had the most consistent and substantial effects on risks. In addition, use of an additional worker consistently reduced risks across several panel sizes and weights, though the benefits differed substantially depending on the specific tasks performed. While such findings indicate potential control approaches (e.g., use smaller panels and more workers), they may adversely affect productivity. A more systematic approach, facilitated by the DSS, will thus be needed to address ergonomic and productivity jointly.

Panelization Construction Design and Planning Algorithms

The overall design and planning process for panelized residential construction can be divided into three closely related problems: panelization, stacking, and construction planning. Our approach is based upon lean manufacturing and stems from several fundamental concepts:

- Stacking is based upon build order. In other words, the "top" panel of each stack is always the next one needed/used. Workers no longer slide panels off to the side or onto the floor to get to the panel they need. Only those panels being worked on are out of the stack, and the work area is kept neat and tidy (lean principle: 5S). This accelerates construction and also eliminates safety hazards resulting from panels left lying on the ground or tipped against walls.

- Once a panel is removed from a stack, it is processed in one continuous operation (barring a change of workers) until it is fixed at its final position (lean principles: one-piece flow, minimize setups).

- Workers involved with a given panel can change between construction tasks (e.g., from lifting the panel off the stack to carrying it) to best suit the requirements of a given panel/task combination (lean principle: shojinka).

- Connectivity is maintained to the extent possible – each panel, save the first, is preceded by ≥ 1 connecting panels. This simplifies positioning and minimizes the need for temporary bracing of stand-alone panels; thereby panels are installed quickly and correctly the first time (lean principle: jidoka).

- A single build pattern is used (e.g., left-to-right and front-to-back), as much as possible, to avoid workers being trapped or boxed-in.

- Upon delivery, all stacks are dropped off along the same edge of the structure ("dropping edge").

Panelization. Panelization consists of "breaking up" the walls or dividing them into panels. The process employs three parameters: stud spacing, preferred panel length, and maximum panel length. Based upon these parameters, walls are divided into panels. The build direction is taken into consideration to ensure smooth construction in the field and to minimize ergonomic impact. Of note is that the panelization plan (and hence stacking formulation, construction sequence, etc.) varies with build direction. Thus, a panelization plan is created for each feasible build direction (input by the user). Remaining problems are then solved for each panelization plan, and the best overall solution is selected.

Stacking. A heuristic method employing a staged approach has been developed for stacking. In brief, we divide the building into zones running parallel to the dropping edge. Each zone has an unload area along the dropping edge – where panels can be unloaded from a stack without interfering with any finished panels – and one or more associated build areas. Stacks are dropped off at each unload area in turn. Panels within the associated build areas then form a continuous build sequence (and connect with the previous build areas). Once zones are established, the corresponding build area panels are assigned to stacks by moving through the build areas according to the build direction and selecting panels based upon their final location in the build area. This approach ensures that panel connectivity is maintained as much as possible and that a feasible build sequence results. Stack locations and delivery sequence are automatically generated, and the results minimize move distances for panels within each stack. Delivery of select stacks can be overlapped, if desired, to allow two stacks to be worked on simultaneously. Compared to the traditional approach (fill stacks as much as possible to minimize trips to the worksite), our methods can yield a larger quantity of stacks, each filled to a lesser extent. More trips are not a necessary outcome, however, as multiple, partially filled stacks can be loaded onto the same truck. Computational evaluations have indicated that our current algorithms, compared to current methods (using commercial software and manual adjustments), can concurrently reduce the number of stacks and material handling requirements (i.e., weighted distances).

Construction Planning. The stacking heuristic assigns panels to stacks to maintain connectivity and provide a feasible build sequence. Thus, no on-site construction sequencing is necessary. To get each panel from its initial location/orientation on a stack to its final location/orientation in the building, a sequence of construction tasks is required. These are based upon a construction task taxonomy developed from analysis of extensive field observations. In addition, there is a set of possible task sequences, along with the allowable worker quantities for each task. As previously described, we allow the workers involved with a panel to vary from one task to the next.

The construction task planning, scheduling, and worker assignment problems are difficult to solve. Construction scheduling alone closely resembles traditional *job-shop scheduling*; as such, the three problems together will be at least as hard to solve as job-shop scheduling problems. One widely used and well-studied approach for job shop scheduling is the use of dispatching rules: whenever a job is completed at a machine a simple rule (e.g., shortest processing time) is used to select the next job to run. We employ this same approach via the use of construction rules that can be easily employed by workers in the field. Such rules are needed to establish (i) *what panel* to work on next, when a worker becomes available, (ii) *how many* workers to use for each panel task, and (iii) *which* workers to use for each panel task once the quantity has been established. For example, we may elect for a worker to always go to the nearest panel being worker on, select the maximum quantity of workers for each panel task, and then select the actual workers to use to balance workload (utilization).

4. Summary and Future Work

There is an increasing trend toward premanufacturing in construction, including the use of panelized walls. Current panel design approaches lead to both inefficiency and WMSD risks, negating some of the expected cost reductions intended by panel use. The centralization of panel design, however, provides an opportunity to enhance such efficiencies and reduce ergonomic exposures. We have developed a prototype DSS for panelized residential construction that facilitates a proactive approach to ergonomics and addresses the ongoing need for appropriate design tools to facilitate PtD. As it incorporates ergonomic aspects throughout the construction process, the overall impact of DSS use is expected to be more efficient and effective than reactive, site-based interventions applied only later in the product life cycle. A primary advantage in our approach is the inclusion of both ergonomics and productivity as fundamental components and the joint improvement of both. As such, our approach addresses the need to support the economic/business case for PtD, specifically by providing information relevant to necessary financial considerations in decision-making and an understanding of the financial implications of PtD. Our system also serves as an "integrating mechanism"; from a sociotechnical systems perspective, such mechanisms help overcome the traditional challenges involved when there are multiple functional units (Hendrick and Kleiner, 2001), such as architects, engineers, and builders in construction. Finally, several authors have noted current research and practice needs related to interventions, specifically the dearth of available solutions and the lack of high-quality evaluative studies (van der Molen et al., 2007; Watterson et al., 2007; Lehtola et al., 2008; Rinder et al., 2008). Our DSS, from conception, was intended to address these needs by facilitating the development and assessment of interventions to reduce ergonomic exposures and risk.

Much additional work is needed, however, and is proceeding in several directions. First, the decision-making logic in the DSS and the ability to simulate and visualized tasks is being improved and evaluated. Use of the DSS requires specific design/construction rules, and simulation is then used to establish how panels are design and shipped and how construction proceeds. Based on lean principles and input from panelized construction workers and supervisors, a wide variety of such rules will be evaluated. To improve usability and validity, detailed simulation input data are being compiled from field observations and lab studies, and WMSD risks are being estimated for a wider range of construction activity using lab-based task simulations. Second, there is a need to determine effective strategies for implementing the DSS in practice and improving the business case for its actual use. This will involve consultations with potential users (panel designers, manufacturers, and contractors). Computer-based cases studies will be conducted to compare panelization and stacking plans generated using the DSS vs. those from the “traditional approach. A more “upstream” focus is also needed, to determine the impacts of DSS use on panel manufacturers and shippers. Third, a field study is planned to demonstrate and quantify the potential and actual benefits of using the DSS.

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