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Development of a decision support system for residential construction using panellised walls: Approach and preliminary results

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There is a high prevalence of work-related musculoskeletal disorders (WMSDs) among residential construction workers, yet control in this industry can be difficult for a number of reasons. A decision support system (DSS) is described here to allow early assessment of both ergonomic and productivity concerns, specifically by designers. Construction using prefabricated walls (panels) is the focus of current DSS development and is based conceptually on an existing 'Safety in Construction Design' model. A stepwise description of the development process is provided, including input from end users, taxonomy development and task analysis, construction worker input, detailed laboratory-based simulations and modelling/solution approaches and implementation. Preliminary results are presented for several steps. These results suggest that construction activities using panels can be efficiently represented, that some of these activities involve exposure to high levels of WMSD risk and that several assumptions are required to allow for ease of mathematical and computational implementation of the DSS. Successful development of such tools, which allow for proactive control of exposures, is argued as having substantial potential benefit.

Keywords: residential construction; ergonomics; task analysis; risk assessment; prevention through design

1. Introduction

An ongoing need exists to reduce the prevalence of work-related musculoskeletal disorders (WMSDs) among residential construction workers. The focus here is on residential carpenters and specifically the process of wall erection using pre-fabricated (panellised) wall systems. In the US, residential building construction is the seventh largest industry, involving about 4% of annual national economic activity (National Association of Home Builders Research Center 2002). Compared to the general workforce, occupational injury rates are high in construction, with over 150,000 non-fatal workplace injuries and illnesses reported in the US in 2005 (Bureau of Labor Statistics 2005). Roughly 20% of these cases were attributed to overexertion and repeated motion. In Washington State, residential building construction was among the three highest industry groups for the most common and costly occupational injury types (Bonauto *et al*. 2006).

Control of WMSDs in construction can be more difficult than in many other industries and a number of authors have highlighted the problems involved. Field studies are hampered by non-continuous employment and a changing and unpredictable workplace (Ringen and Stafford 1996), as well as substantial task variability and irregular work periods (Forde and Buchholz 2004). These, and an often complex project and organisational configuration, make construction a 'demanding section in which to conduct research' and may explain the relative dearth of papers on construction, even with it being a major economic activity around the world (van der Molen *et al*. 2005). As a result, the construction industry has been slow to address construction safety, despite the concerns noted above (Gambatese *et al*. 1997) and the same appears to be the case for ergonomics issues.

Safety in (construction) design has recently been promoted and studied in the construction industry (e.g. Gambatese *et al*. 1997, Gambatese and Hinze 1999, Hecker and Gambatese 2003, Weinstein *et al*. 2005). In this approach, primary attention is given to eliminating hazards through engineering design, with an expectation of improved outcomes relative to other approaches in the hierarchy of control strategies (Roland and Moriarty 1990, Sweeney *et al*. 2000). More specifically, it is argued that construction designers can substantially influence construction site safety by integrating safety considerations during the design process (Gambatese and Hinze 1999). Existing evidence suggests that a substantial fraction of injury-causing accidents stem from conditions

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'upstream' of the actual construction process, at the stages of planning, scheduling and design (Gambatese *et al.* 2005, Weinstein *et al.* 2005). Further, analysis by Hecker and Gambatese (2003) suggests that more than half of construction accidents can be eliminated, reduced or avoided with more attention during design. The approach described here is consistent with the safety in design concept, though modified to address ergonomic concerns.

Panellisation (or panellised walls) refers to one example of the current trend in residential construction toward increasing use of pre-manufactured components. Panellised walls are in contrast to traditional 'stick built' walls, where the latter involves the familiar process of assembling and erecting walls starting from relatively raw lumber. Panels, in contrast, arrive at the work site more completely assembled. A panel designer, working from an architect's drawing, specifies panel sizes (typically lengths) and several aspects of pre-assembly (i.e. from wood only to complete with sheathing, conduit, insulation, etc.). A carpentry crew transfers and erects the panels at required locations on site.

Previous work (Wakefield *et al.* 2001) has documented the present and fairly rapid shift among residential US production builders to panellised forms of construction. Panellisation is also representative of other pre-manufactured construction materials, in that it tends to be a post-design activity undertaken by a subcontractor, who ultimately provides fabrication and delivery services to a site erection subcontractor. This current trend toward panellisation within the housing industry thus provides an opportunity to develop an ergonomic analysis tool, since the centralised panel designer can impact a large number of construction sites and workers.

In this paper, a sequential approach is described to yield a tool that allows panel designers to consider ergonomic risk when developing panel designs. Specifically, it was intended that use of the tool would result in construction plans that reduce exposure to WMSD risks among residential carpenters who use panels. As described, ergonomics issues are incorporated along with more traditional production aspects (e.g. staffing needs, costs, time requirements), in order to increase the likelihood of and decrease impediments to adoption of the tool and to facilitate a larger-scale optimisation of the design–build process. Along with an overview of the approach, preliminary results from several of the steps are provided.

2. Approach

The objective is to develop a computerised decision support system (DSS) for residential construction using panellised walls. Given the building plan (blueprint) for a home, the required decision-making can be divided into two phases: design and planning. The design phase is concerned with establishing the panellisation design: what panels to employ (dimensions, quantity of and location of openings) and the layout (arrangement) of panels. Given a panellisation design, the planning phase then establishes the construction plan: how panels are to be delivered to the site, what construction tasks are necessary and when these tasks are performed and by whom (i.e. construction schedule).

A field study of mechanical installation work has shown that over 50% of the total time observed on construction sites is non-value-adding time in terms of interruption, disturbance, communication and preparation (Vedder and Carey 2005). A good construction schedule can reduce non-value-adding time in construction and thus improve efficiency. To establish how good a particular solution (panellisation design and construction plan) is, three measures are suggested: some aggregate measure of overall ergonomic risk (β); the quantity of workers used (W); and the total construction time (T). The overall objective in design and planning will be to minimise one of the three measures, subject to specified constraints on the other two. Thus, ergonomics aspects are considered directly in formulating the panellisation design and construction plan, an approach that should contribute to improving worker health, safety and performance (van der Molen *et al.* 2005). Previous efforts to develop computer-aided software tools for construction planning (e.g. Chantawit *et al.* 2005) have separated ergonomics aspects from construction planning and scheduling. As previously stated, the goal here is to address ergonomics from the design stage, since such early integration of ergonomics aspects is likely to be most effective (Fadier and Garza 2006).

It is assumed that a finite set of alternative materials and configurations are available for panellisation and that a finite set of generic construction tasks can be identified and quantified, via laboratory-based experiments, with regard to ergonomic risk and performance (i.e. task time). Furthermore, the generic construction tasks and laboratory-based data can be used to generate reasonably accurate, stochastic predictions of ergonomic risk and performance for any particular construction task and panel definition. Additional assumptions are as follows: (i) all workers are identical with regard to risk and performance (to keep the problem manageable); (ii) no defective panels (extremely low defect rates are readily attainable via lean and six sigma programmes at panel manufacturers); (iii) negligible set-up time for all tasks;

(iv) all construction tasks have 100% likelihood of being completed successfully on the first try (i.e. no rework). Each of these assumptions can be relaxed if appropriate data are available.

The assumptions of finite panellisation materials/configurations and quantifiable construction tasks allow panellisation design and construction planning to be modelled as discrete optimisation problems. In each case, a finite quantity of solutions is possible and the objective is to find the 'best' (i.e. optimal) solution. The problems are too large to solve optimally, however, so heuristic (approximate) methods are employed. Different heuristics will result in different solutions (i.e. panellisation designs and/or construction plans) for a given problem. To establish performance (β, W or T) for a given solution, the entire construction process – from panels arriving at the drop-off locations to completion of panellised construction – is simulated. Simulation has been shown to be an effective technique to evaluate decision making on constructions sites (Shi 2003). Here, the simulation will provide not only performance (β, W or T), but also detailed output concerning ergonomic risk, worker utilisations, etc. Additionally, a low-fidelity simulation animation will be possible, allowing the designer to 'see' the construction process in action and get a feel for how the workers must work together, whether some workers appear busier than others, etc.

While the construction tasks for each panel and construction schedule are established as part of construction planning, it is anticipated that simply providing these items to workers and expecting them to follow will not always be feasible. Workers may be unable and/or unwilling to work in this manner, tasks may be short and numerous enough that too much time is wasted checking the schedule, etc. Additionally, emphasising 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 (Nepal *et al*. 2006). An alternative approach will be to provide workers with construction rules, which, when followed, ideally result in the desired assignment of construction tasks and construction schedule. This approach also has the advantage that it allows workers to react to changes and unplanned contingencies that might quickly invalidate plans made in advance.

Based upon the above, the DSS will operate as follows (Figure 1):

(1) The designer first selects the overall (global) objective for the construction problem: minimise overall ergonomic risk β, quantity of workers, W, or total construction time, T. Constraints are then specified for the other two variables.
(2) The designer inputs values for the design parameters (e.g. possible panel drop-off locations).
(3) The designer selects the desired solution methodology (i.e. particular combination of solution methods) to be used. This is explained in detail in section 6.
(4) The DSS then outputs: (i) the panellisation design and construction plan; (ii) the value of the selected objective variable (β, T or W). The designer can then view a simulation animation of the construction process, if desired. Additional output (e.g. ergonomic risks and worker utilisations) is also available for in-depth analysis.
(5) If desired, the designer changes the solution methodology (i.e. one or more solution methods) and re-runs the problem through the DSS.
(6) The designer evaluates all solutions generated and selects the most appropriate one.

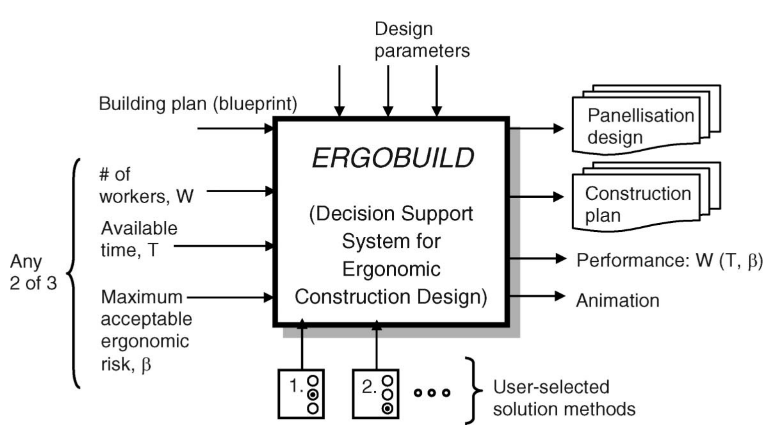

Figure 1. Top-level input/output diagram for decision support system.

Once the above process is complete, the results are used as follows. The panellisation design, panel drop-off locations and panel stacking order at each location are provided to the panel manufacturer and transport company (if an external agent is used), so the panels can be manufactured and delivered accordingly. If deemed practical, the construction tasks for each panel and construction schedule can be forwarded to the construction site for the workers to follow in building the house. Otherwise, the construction rules employed for the chosen solution are provided to the job site and communicated to the workers, who then perform their own decision making during the building process.

To implement the above approach, several tasks are necessary. Broadly speaking, the tasks can be divided into three categories: (i) generic modelling of construction tasks (lift panel, move panel, etc.) and laboratory-based generation of ergonomic and performance data for such tasks; (ii) modelling and solution of the panellisation design and construction planning problems, via the generic construction tasks and ergonomic/performance data from (i); (iii) implementation of (i) and (ii) via the DSS.

In the following sections, a summary is first provided of input obtained from designers that will be used to guide DSS development. An overview is then given of the approach to generic modelling and laboratory-based data collection, followed by a description of how the panellisation design and construction planning problems are addressed.

3. Input from end users

As defined by Gambatese (2000), most design–bid–build project delivery efforts include a 'designer' who is a professional with expertise in one of several disciplines (e.g. architecture, structural or mechanical engineering, etc.). Given the focus on a proactive (design-based) approach vs. one that relies on the behaviours of workers and given that designers are ultimately the individuals who can ensure that delivered construction materials can be safely assembled into end products, the residential construction designer (in particular the panel designer) is considered to be the end user. This is not to ignore the on-site construction workers, as their health and safety is the end goal (see section 4.3 for results concerning worker perceptions of physical demands).

The present authors seek to take advantage of the knowledge and experience of panel designers and to ensure that the end product is both usable and useful. Given the intent to incorporate ergonomics in panel design, there was thus a need to determine the following among panel designers: knowledge of ergonomics; perceived barriers to including ergonomics into design; and opinions regarding whether ergonomics has a role in design. In addition, current practices needed to be identified, including whether there are existing penalisation design rules, principles and practices.

An investigation has recently been completed into these issues (Kim *et al.* 2008) with a sample of panel designers in the eastern US. They reported having little knowledge about ergonomics or the potential impact of their panel designs on the ergonomic risks incurred by construction workers. As a whole, they were neutral or slightly resistant to incorporating ergonomics in their designs, primarily due to a perceived lack of responsibility for worker health, limited potential influence and an anticipation of increased workload and costs and decreased flexibility. They were also neutral to slightly negative regarding the feasibility of including ergonomics in their designs, yet most agreed on the necessity to reduce health and safety risks. Any software tool that incorporates ergonomics must address and/or overcome these perceptions and beliefs.

Results from this investigation also highlighted that software must also accommodate or address current design practices. Panel designers indicated that transportation and stacking issues were key in driving decision making and that panel weight and crew size were low in importance. The latter two would appear to be of greatest consequence for ergonomic exposures. Panel manufacturers also have standard panel dimensions, which are based on shipping costs, trucking capacity, standard lumber dimensions, etc. These must be accommodated, in order to avoid excessive increases in manufacturing costs.

4. Taxonomy and task identification

Even with the relatively narrow scope of panellised wall construction, the discrete tasks used and variability of methods employed are likely extensive. In order to ergonomically assess panellised construction methods, a descriptive approach is first required, to yield an understanding of the process and the specific tasks involved. Findings from such a descriptive approach can then guide more detailed investigations, as hazard identification should precede exposure measurements (Schneider and Susi 1994).

Therefore, this step had three objectives. The first was to develop a taxonomy of the panel erection process. A broad or taxonomic approach permits more complete hazard identification by characterising the process and identifying frequently performed tasks with high-risk exposures (Moir *et al.* 2003). The second objective was to provide a descriptive basis for detailed laboratory-based biomechanical analysis of identified tasks, specifically the characteristics of panel erection tasks involving manual material handling. The third objective was to obtain preliminary indications of which tasks involved the highest levels of physical demands, in order to focus the subsequent laboratory-based simulations.

Wall panels are delivered to a work site as pallets, containing 15–40 panels, with a height of 1–3 m. Panel erection involves a relatively consistent set of procedures. Prior to panel erection, workers draw panel layout lines and mark panel numbers on the floor, according to panel layout drawings that come with panel stacks. The layout lines indicate the actual location of each panel, and the panel number matches with the number labelled on the panel. Afterwards, panel stacks are placed either on the floor or near the floor using a forklift, and workers erect panels in designated locations.

Taxonomic description and assessment of task characteristics were based on video recordings obtained during the framing phase of 10 different home building sites in the Washington, DC area. Both single family and town homes were visited and crew sizes ranged from three to eight workers. Panel erection was recorded for the first or second floor, depending on the site and status. Prior to any video recording, an informed consent procedure was completed that was approved by the local Institutional Review Board (IRB).

4.1. Hierarchical task analysis

Hierarchical task analysis (HTA) was used to develop a taxonomy of the panel erection process. HTA is a broad approach that can effectively organise diverse subtasks of the task of interest (i.e. operations) and can establish conditions that determine when subtasks are carried out to achieve operating goals (Kirwan and Ainsworth 1993). Overall, HTA is a hierarchical tool used to develop a description of the task in terms of operations and conditions. Operations are simply referred to as subtasks that constitute a task of interest (hereafter the term task is employed instead of operation for simplicity). A series of conditions is, in general, referred to as a plan. In the current taxonomy, two conceptual levels (i.e. tasks and subtasks) were used and two functional categories were introduced (fundamental and supplemental) as described below.

Tasks are central to developing a HTA. Tasks can be defined as a sequence of subtasks and/or activities performed by an individual or a group of workers to accomplish a specific purpose (Moir *et al*. 2003). Tasks in the panel erection process were identified by review of the video recordings. The name of each task was selected to conform to an operational goal of the task. A task was further divided into subtasks and multiple levels of subtasks were defined, depending on the level of detail required (or of interest). Separate tasks could share the same subtask.

Here, subtasks were considered equivalent to activities defined by Moir *et al*. (2003). Subtasks were characterised by a series of physical actions (e.g. lifting, lowering, twisting, etc.) that an individual worker performs to attain a simple work goal and that are transferable from one worker to another. Subtasks were identified when an important change in a series of physical actions was observed. In the panel erection process, a group of workers usually performs a subtask that includes multiple activities. For example, when nailing down a panel, one worker performs a hammering activity while other workers perform a holding activity to keep the panel in position.

Tasks, including their subtasks, were categorised into fundamental tasks and supplemental tasks in order to discriminate tasks that are sequential and commonly observed on every site from tasks that are non-sequential and not commonly observed. That is, fundamental tasks are defined as required tasks that are sequentially completed for panel erection. In contrast, supplemental tasks are conditionally done during the course of panel erection, depending on house type, builder practice, etc.

Primary handling techniques for lifting, carrying, erecting, moving and lowering activities were identified from review of the video records. Table 1 shows the coding system used and also specifies and describes alternative techniques employed. Panel erection could be comprehensively represented by four fundamental and 10 supplemental tasks (a hierarchical diagram of which is given in Figure 2). The fundamental task plan is represented as a flowchart (Figure 3), indicating the order in which fundamental tasks are performed and how the supplemental tasks are interrelated. Similar plans were derived for each of the fundamental and supplemental tasks and subtasks.

4.2. Task characteristics

While a HTA can describe how and what activities workers actually perform to accomplish the given task, it does not provide detailed quantitative data on how often or how long a certain task, subtask or activity is conducted. In order to facilitate a better identification of exposures to ergonomic risk factors and guide subsequent laboratory-based analyses, additional measures were obtained from manual materials handling tasks: primary panel handling techniques; the number of workers; type of panel; time duration; frequency of each of the identified tasks and subtasks. These were obtained after the HTA was completed; in essence, the HTA served as a framework for the

Table 1. Coding and descriptions of primary panel handling techniques.

Activity	Technique	Description	Notes
Lifting	L1	Lift panel while it is oriented horizontally	Eight initial hand positions
	L2	Lift panel while orientating it vertically, so that panel is held vertically at completion of lifting	
Carrying	C1	Carry panel while in a horizontal orientation	
	C2	Carry panel while in a vertical orientation	
	C3	Carry panel oriented vertically while held slanted over the shoulder	
	$C4_{A/B/C}$	Only for a single worker, while other carrying techniques may be done by a single or multiple workers $C4_A$: worker carries unsheathed panel or panel with opening on one shoulder with the arm around the opening of a panel $C4_B$: worker carries panel by holding panel over the shoulder $C4_C$: worker carries panel by grasping one side of panel	
Moving	M1	Push/pull panel while it rests on the deck in a vertical orientation	
	M2	Push/pull panel by holding up one side of the panel while the other side rests on the deck	
	M3	Push/pull panel without lifting	
Erecting	E1	Lower one side of panel to touch the deck and push upward on the panel until it stands vertically	Five initial hand positions
	E2	Rotate panel to a vertical orientation without touching the deck	
Lowering	LW	Lower panel onto the floor	

assessment of task characteristics. Primary panel handling techniques and associated activity duration were identified for lifting, carrying, moving, erecting and lowering activities. Task characteristics were determined separately by two investigators and cross-checked to ensure consistency and minimise errors.

Time duration was recorded (from review of the videotapes) only for actual physical efforts; the time required to formulate a work sequence or to interpret a panel layout drawing was not taken into account. In addition, time duration for two work activities was not measured: simple tape measurements without handling of panels or hand tools; and cutting a lumber plate or a piece of lumber to a certain length. The former did not involve any physically demanding activities and the latter was excluded due to difficulties in tracking all the workers on site. In addition, the time involved in descending a ladder was disregarded because workers were frequently observed to stay on a ladder after completing a job or task.

A total of 1443 panel handlings were recorded and frequencies identified for alternative techniques, panel types and other relevant dimensions (e.g. initial hand position, transfer distances, etc.). Examples of two lifting techniques observed are provided in Figure 4. Results for lifting, erecting and lowering are summarised in Table 2, while those for carrying and moving are in Table 3. Overall, the dominant technique for each handling activity was different according to panel type. A review of the video records, however, showed that lifting and carrying techniques tended to change as the panel erection process advanced. For example, techniques using a vertical panel orientation are more often employed in the later phases, since working space becomes limited by panels already installed.

Time durations were obtained from 1321 fundamental and 614 supplemental tasks. Summary statistics for the fundamental tasks are given in Table 4, with similar results available for the supplemental tasks. In some cases, tasks were inseparable, in that they are done simultaneously or the time duration of one task is extremely short compared to the other task. For example, F4.1.1 (pick up panel) + F4.1.2 (carry panel) indicates that workers carry a panel after lifting the panel off the floor. A transition from lifting to carrying often could not be clearly identified. In these cases, a '+' sign is used in Table 4 and time duration is considered an aggregated duration for the completion of both tasks.

4.3. *Worker questionnaires*

A questionnaire was developed to gather opinions of construction workers regarding the physical demands associated with panel erection tasks. Illustrations of the fundamental and supplemental tasks identified above were provided and participants rated their perceptions of the overall physical difficulty of each task using a 5-point scale (1 = not demanding to 5 = extremely demanding). In addition, participants indicated which three tasks were thought to be the most physically demanding. Additional questions asked which tasks/subtasks could lead to injuries

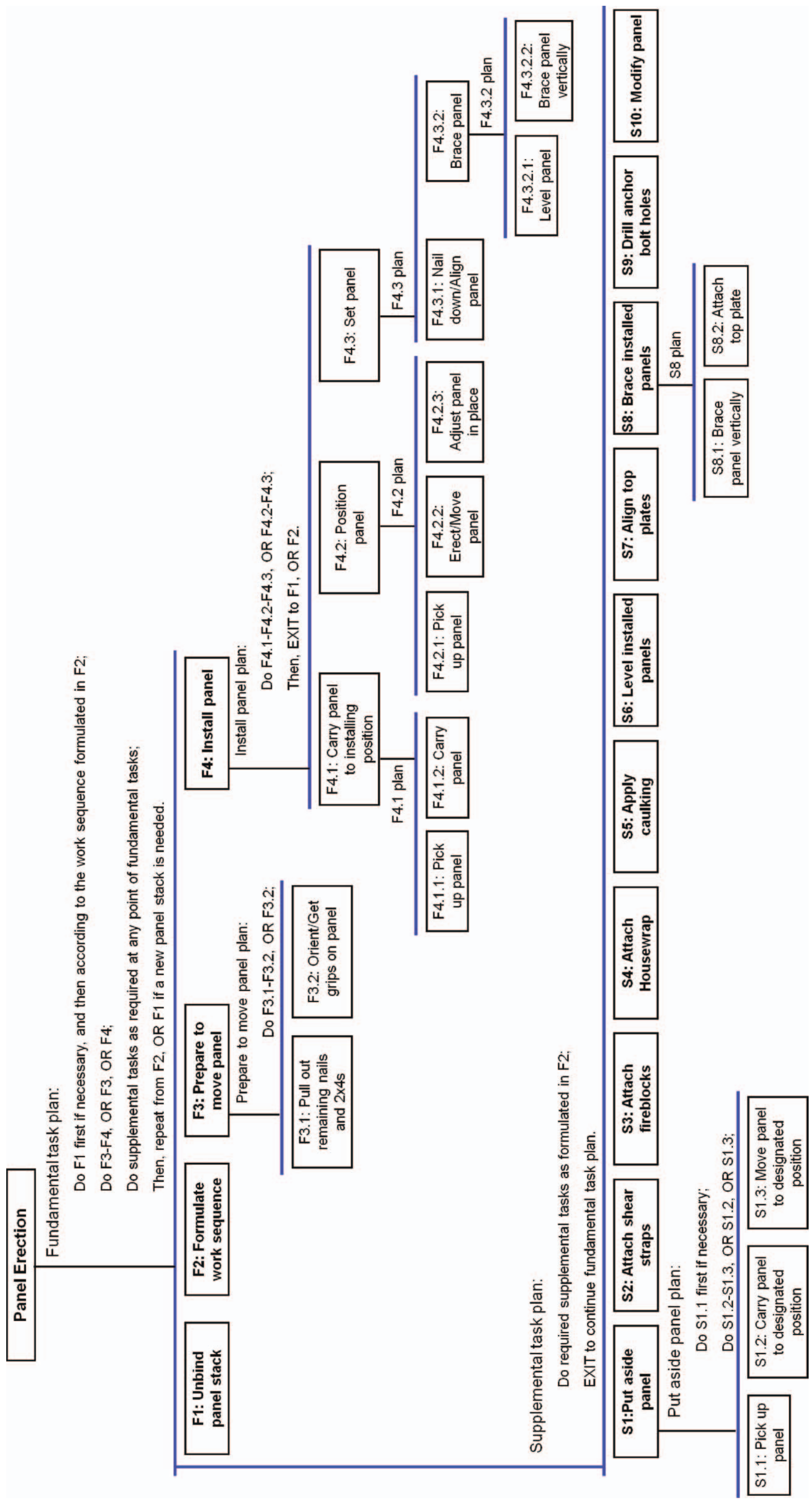

Figure 2. Hierarchical diagram for panel erection.

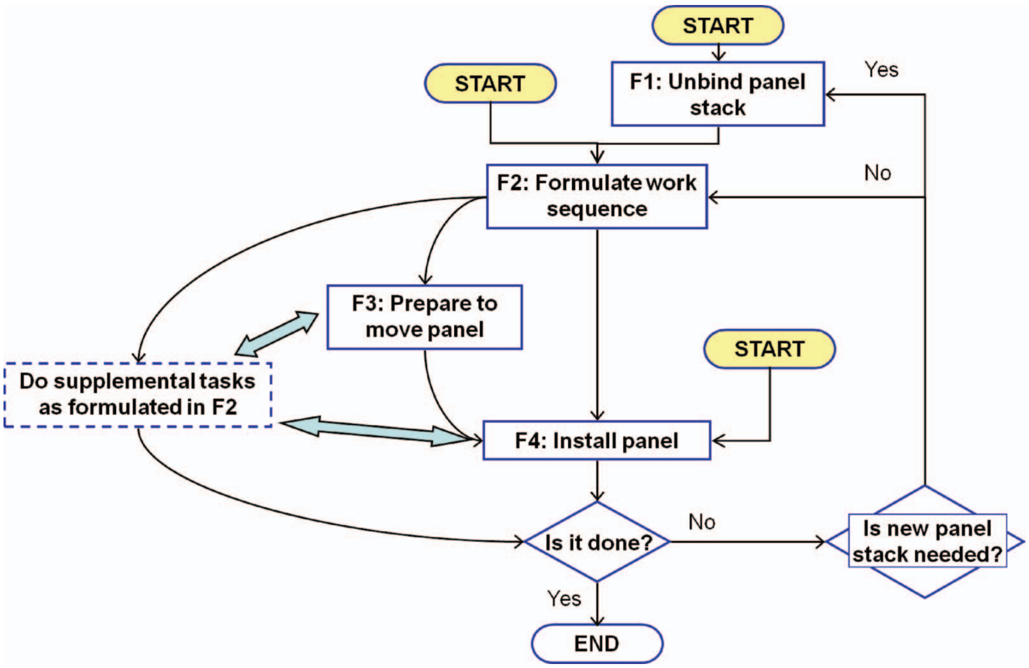

Figure 3. Flowchart of fundamental task plan. Panel erection can be completed by beginning the process from three different starting points.

during installation, in which body parts they experienced soreness or pain during or after panel installation and aspects of a panel that increased physical demands. Field managers in residential home building companies in the Washington, DC area distributed the questionnaire to individual carpenters (both an English and a Spanish language translation were made available), and 18 responded.

Across the different tasks, carrying a panel and modifying a panel on site were rated the most difficult, with mean responses of 3.7 and 3.6, respectively. Carrying (78%) and modifying (39%) panels were also selected as the most and second most frequently indicated as most physically demanding, with erecting a panel selected third most frequently (33%). Carrying and erecting panels were the tasks most frequently indicated (78% and 57%, respectively) as potentially leading to injury. Body parts most frequently identified were the lower back (50%), upper back (22%) and arms (22%). Several aspects of panels were identified as increasing physical demands, the most frequent being the large size of panels (83%), high weights (50%), panels that do not fit properly (33%) and difficulty in handling (17%).

5. Laboratory-based task simulation, exposure assessment and risk assessment

From the HTA, identified task characteristics and worker questionnaires, information is available regarding necessary and optional tasks, task sequencing, differences and relative frequencies of alternative techniques and the relative physical demands related to primary wall erection tasks. This information, though somewhat crude, can be used to develop higher-fidelity laboratory-based simulations. Doing so allows for more detailed measurements of exposures, which would otherwise be difficult to obtain in the field.

The design of such laboratory-based simulations should achieve two goals. First, the tasks should be simulated with a reasonable level of detail and accuracy. Wall erection at a construction site can involve material spread widely and rising multiple stories, yet few laboratories have such available space. It is thus planned to simulate only elemental tasks, specifically those identified from the field observations. Further, the simulations will include alternative methods used (e.g. horizontal and vertical lifting, Figure 4). As not all tasks and alternatives can be feasibly examined, a limited set of simulations will be achieved by identifying combinations that involve apparent physical demands and occur with some frequency. Second, the simulations and exposure assessment should facilitate subsequent ergonomic risk assessment. Indicated below is a set of risk assessment tools that have been identified. Laboratory-based measurements must provide the necessary data as input to these tools. Further, it would be prudent to obtain measures for more

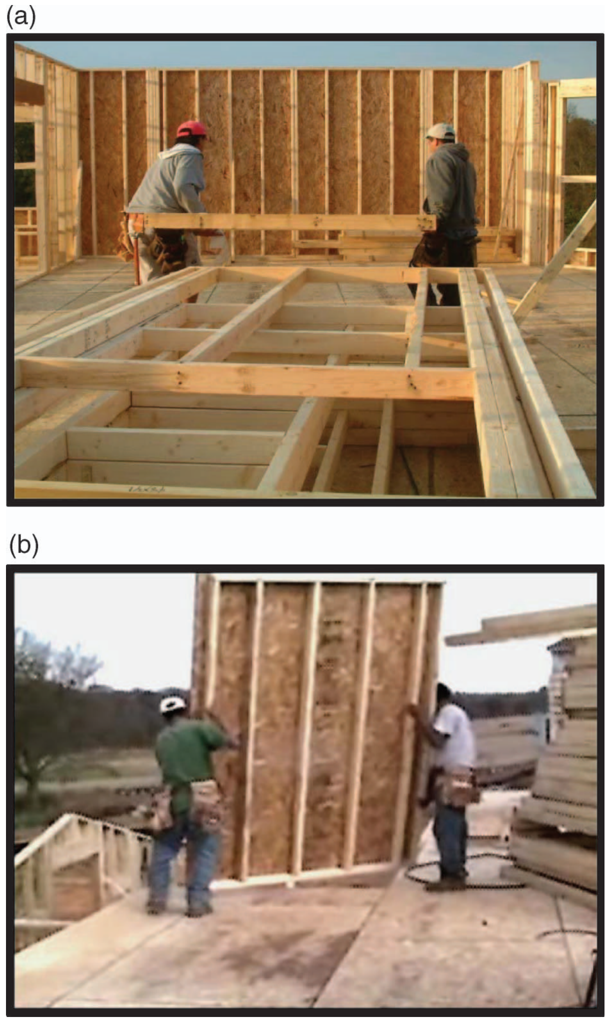

Figure 4. Illustration of two lifting methods. (a) L1; (b) L2. Carrying techniques (C1 and C2) are extensions of lifting methods L1 and L2, respectively.

advanced tools, as well as for future tools that may be developed.

A set of measures are planned to achieve these goals and that can be broadly categorised as anthropometric, kinematic, kinetic and electromyography (EMG). In all cases, methods to obtain these are fairly standardised and no fundamentally novel approaches seem needed. Anthropometric descriptions allow both for comparisons of experimental and worker populations and serve as input for determining subsequent measures. Kinematic measures (posture and motions) will be obtained to represent the body as a system of linked segments. External kinetics (forces and moments) will be obtained using a combination of load cells (attached to panels) and force platforms. From these data, inverse dynamics analyses will be used to estimate 3-D dynamic external moments at major joints (ankle, knee, hip, lumbar spine, shoulder, elbow, wrist). Finally, activity of major torso muscles will be monitored from surface EMG, to allow for estimates of spinal loading.

Multiple and diverse ergonomic assessment methods are available. A subset has been selected to achieve three ends: specifically, ease of implementation; common use; and relevance to panellised wall erection. These methods are not intended as complete, but rather as broad and representative, with each providing distinct output for ergonomic evaluation.

Psychophysical limits and two rapid assessment tools will used to obtain overall evaluations of the lifting tasks. Psychophysical limits (e.g. Snook and Ciriello 1991) are based on studies in which participants determined maximal acceptable levels of physical effort. RULA (McAtamney and Corlett 1993) and REBA (Hignett and McAtamney 2000) allow for assessments of limb postures and loads. Although alternative methods exist, and there is limited validation of these methods to predict injury risks, they are selected based on common use and incorporation of generic injury risk factors.

Two more quantitative approaches will be based on joint strength demands and an existing guideline for manual lifting. Strength demands refer to the external moments imposed by the panel erection tasks, relative to population capacity (strength). The former is obtained during the laboratory-based simulation, while the latter is available in software (e.g. The University of Michigan 3DSSPP^{TM}). The National Institute for Occupational Safety and Health (NIOSH) lifting equation (Waters *et al*. 1993) will be used to assess lifting tasks, based on widespread use and incorporation of primary risk factors.

Preliminary results have been obtained using the NIOSH lifting equation applied to 174 observed panel lifts. Both one- and two-person lifts were analysed for two types of lifts (L1, panel held horizontal; L2, panel held vertical). Video records, along with panel layout drawings, were used to estimate distance-related multipliers. Asymmetry was estimated by observation, while coupling was set as 'fair'. Frequency multipliers were all set equal to one. Panel masses were estimated from the panel dimensions and data provided by O'Brien *et al*. (2000). This report, however, did not provide estimates of masses for exterior walls with openings; masses were thus conservatively approximated assuming no openings. Actual masses were likely only slightly overestimated, as header material adds additional mass when openings are present. Results indicated that lifting indexes were often quite high and <1 only for a small proportion of small panels (Figure 5). A given panel mass also resulted in a significantly higher lifting index when a vertical lift was performed.

An EMG-based model (e.g. Cholewicki *et al*. 1995, Nussbaum and Chaffin 1998, Staudenmann

Table 2. Primary panel handling techniques (lifting, erecting and lowering).

Activity	Technique	Panel type*	Initial hand position	Number of workers mean (min, max)	Total observations
Lifting	L1: 191 (50.7%)	A: 63 (33.0%)	Ground: 58 (30.4%)	2 (1, 4)	377
		B: 47 (24.6%)	Knee: 48 (25.1%)	2 (1, 3)	
		C: 81 (42.4%)	Knuckle: 37 (19.4%)	2 (2, 4)	
			Elbow: 34 (17.8%)	2 (1, 5)	
			Shoulder: 10 (5.2%)	2 (1, 3)	
			Above shoulder: 4 (2.1%)	2 (1, 3)	
			Below ground: 1 (0.5%)	1 (1, 1)	
	L2: 186 (49.3%)	A: 29 (15.6%)	Ground: 60 (32.3%)	1 (1, 3)	
		B: 23 (12.4%)	Knee: 19 (10.2%)	1 (1, 2)	
		C: 134 (72.0%)	Knuckle: 15 (8.1%)	1 (1, 2)	
			Elbow: 44 (23.7%)	1 (1, 3)	
			Shoulder: 27 (14.5%)	2 (1, 3)	
			Elbow-Waist/Knee†: 20 (10.8%)	2 (1, 3)	
Erecting	E1: 165 (81.7%)	A: 54 (32.7%)	Ground: 35 (21.2%)	2 (1, 4)	402
		B: 37 (22.4%)	Knee: 12 (7.3%)	2 (1, 4)	
		C: 74 (44.8%)	Knuckle: 43 (26.1%)	2 (1, 4)	
			Elbow: 49 (29.7%)	2 (1, 4)	
			Shoulder: 26 (15.8%)	2 (1, 3)	
	E2: 37 (18.3%)	A: 5 (13.5%)	Knuckle: 5 (13.5%)	2 (1, 3)	
		B: 4 (10.8%)	Elbow: 22 (59.5%)	2 (1, 3)	
		C: 28 (75.7%)	Shoulder: 10 (27.0%)	1 (1, 2)	
Lowering		A: 33 (26.8%)		2 (1, 5)	123
		B: 25 (20.3%)			
		C: 65 (52.8%)			

*Type A: exterior wall with opening; type B: exterior wall without opening; type C: interior wall.
†One hand placed at elbow height, the other at waist or knee height.

Table 3. Primary panel handling techniques (carrying and moving).

Activity	Technique	Panel type*	Transfer distance (m) Mean ± SD	Duration (s) Mean ± SD	Number of workers mean (min, max)	Total observations
Carrying	C1: 165 (41.0%)	A: 59 (35.8%)	3.8 ± 2.7	11 ± 7	2 (2, 5)	402
		B: 44 (26.7%)				
		C: 62 (37.6%)				
	C2: 46 (11.4%)	A: 2 (4.3%)	3.3 ± 2.3	9 ± 5	2 (2, 3)	
		B: 3 (6.5%)				
		C: 41 (89.1%)				
	C3: 85 (21.1%)	A: 3 (3.5%)	4.2 ± 3.0	9 ± 7	2 (2, 3)	
		B: 3 (3.5%)				
		C: 79 (92.9%)				
	$C4_A$: 51 (12.7%)	A: 3 (5.9%)	3.9 ± 2.0	9 ± 4	1 (1, 1)	
		B: 3 (5.9%)				
		C: 45 (88.2%)				
	$C4_B$: 39 (9.7%)	B: 3 (7.7%)	3.6 ± 2.4	9 ± 7	1 (1, 1)	
		C: 36 (92.3%)				
	$C4_C$: 16 (4.0%)	A: 1 (6.3%)	4.6 ± 3.7	7 ± 4	1 (1, 1)	
		B: 3 (18.8%)				
		C: 12 (75.5%)				
Moving	M1: 252 (74.3%)	A: 55 (21.8%)	1.9 ± 1.85	8 ± 8	2 (1, 4)	339
		B: 34 (13.5%)				
		C: 163 (64.7%)				
	M2: 80 (23.6%)	A: 29 (36.2%)	1.7 ± 1.2	6 ± 4	2 (1, 3)	
		B: 16 (20.0%)				
		C: 35 (43.8%)				
	M3: 7 (2.1%)	A: 5 (71.4%)	1.5 ± 1.2	7 ± 6	1 (1, 2)	
		B: 1 (14.3%)				
		C: 1 (14.3%)				

*Type A: exterior wall with opening; type B: exterior wall without opening; type C: interior wall.

et al. 2007) will be employed to obtain more refined estimates of low back loading and injury risk (i.e. compression and shear forces). An EMG-based approach can directly account for individual differences and is feasible since EMGs are obtained in the laboratory-based studies. A final model will be employed to assess postural stability. Falls are the leading cause of death, accounting for roughly one-third of all worker fatalities (Occupational Safety and Health Administration 1990, Hinze 1997). In construction, a large fraction of falls are directly related to material handling (Pertulla *et al.* 2003, Fredericks *et al.* 2005). Loss of balance is considered an important causal factor (Hsiao and Simeonov 2001) and preliminary work suggests that workers are frequently exposed to fall hazards during panel erection (Kim *et al.* 2006). Although postural stability is a broad construct, it can be operationally defined as the fraction of the base of support traversed by the body centre of mass (e.g. Holbein and Redfern 1997, Chow *et al.* 2005) or by the control of linear and angular momentum (e.g. Commissaris and Toussaint 1997).

Table 4. Time durations for fundamental tasks.

Fundamental task	Time duration (s) Mean ± SD	Minimum duration (s)	Maximum duration (s)
Unbind panel stack (F1)	144 ± 76	57	253
Prepare to move panel (F3)			
F3.1	39 ± 24	7	88
F3.2	29 ± 37	9	135
Carry panel to installing position (F4.1)			
F4.1.1 + F4.1.2	16 ± 5	6	23
F4.1.2	14 ± 6	7	26
Position panel (F4.2)			
F4.2.1 + F4.2.2	36 ± 21	17	88
F4.2.2	18 ± 6	10	26
F4.2.3	38 ± 12	23	64
Set panel (F4.3)			
F4.3.1	47 ± 20	20	80
F4.3.2.1 + F4.3.2.2	67 ± 56	23	130
F4.3.2.2	31 ± 32	13	85

Note: See text for note regarding ' + ' signs.

6. Modelling and solution of panellisation design and construction planning problems

As outlined in section 2, the decision making required for residential construction using panellised walls can be divided into panellisation design and construction planning phases. To improve tractability (i.e. ease of solution), construction planning itself can be decomposed into several smaller problems. The result is six separate sub-problems for residential construction using panellised walls, summarised as follows:

(1) Panellisation design – panel specifications (dimensions, openings, etc.) and layout.
(2) Panel stacking – how panels are arranged into stacks for delivery to the construction site.
(3) Stack locating – drop-off location for each stack at the construction site.

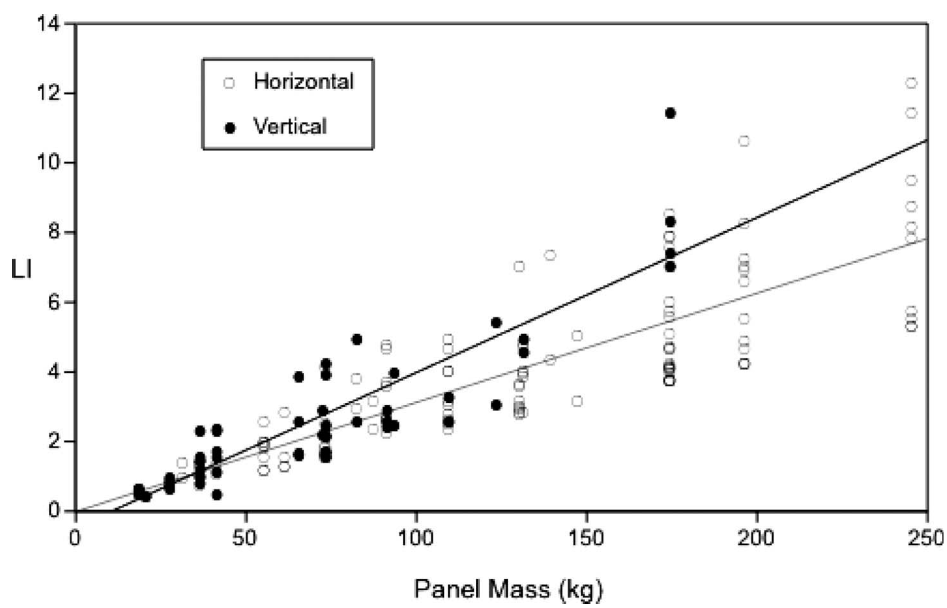

Figure 5. Lifting indexes (LI) as a function of panel mass, using two different lifting methods. Linear trends are illustrated for the two lifting methods.

(4) Stack delivery sequencing – precedence constraints specifying which stacks must arrive before which other stacks at the construction site.
(5) Construction task planning – construction tasks (lift, move, tilt, etc.) and their sequence for each panel.
(6) Construction task scheduling – which construction tasks are to be done when and by which worker(s).

The decomposition approach improves tractability, but has a drawback. Even if an optimal solution is found for each sub-problem, there is no guarantee that the combination of local optimal solutions will result in a global optimum. Thus, while each sub-problem is addressed independently (sequentially), the resulting solution cannot be completely evaluated at that stage; one can only evaluate how good the global (overall) solution is once all sub-problems have been solved. Furthermore, because global optimality cannot be guaranteed, it is desirable to have alternate solution methods (heuristics) available for each sub-problem. A particular combination of solution methods – one for each sub-problem – constitutes a solution methodology. For a given construction problem, many solution methodologies are possible. The end user must evaluate the appropriateness of the solution (panellisation design and construction plan) and adjust the solution methodology as deemed necessary, as described in section 2. A brief overview of the modelling and solution approaches for each sub-problem now follows.

6.1. *Sub-problem 1: Panellisation design*

While there is no clear-cut objective in designing panels, the impact of panellisation design is obvious: employing larger-size panels means fewer trips but panels are heavier, and vice versa. The decision logic for panellisation can be established based upon user input (section 3) and detailed analysis of the problem. For example, panel lengths are to be in increments of 4′ whenever possible, panel breaks must be some minimum distance from corner joints and openings such as walls and doors should be placed in large panels (as opposed to small) to reduce weight where most beneficial. A choice of design parameters can then be established to specify the panellisation procedure exactly. Example design preferences include selection of maximum panel size (12′, 16′ or 20′), preferred panel size (8′, 12′, 16′ or 20′) and where to place remainder panels (left end, right end or middle of wall).

6.2. *Sub-problem 2: Panel stacking*

Once panels are produced, they are stacked together for delivery to the job site. One must establish: (i) how many stacks; (ii) the panels in each stack; (iii) the stacking order for each stack. The panellisation plan is divided into construction zones where all panels within a zone form a continuous build structure. The panels comprising each zone then form a different stack. Next, the build sequence for the panels in each zone is established; panels are then placed in this same order in the stack to allow for continuous flow during construction. A build sequence is feasible if: (i) each panel connects to at least one panel already in place; (ii) no panel blocks the path needed for a subsequent panel (i.e. no 'traps'); (iii) no panel goes in-between panels already in place (i.e. no 'squeeze fits'). The objective is to minimise stack start delay: the time workers must wait, once a subsequent stack arrives, before it can be started. If a panel is to connect to another panel already in place, there is increasing delay if the panel is farther down the stack. To help study this problem, a preliminary integer programming model has been developed (see Appendix 1). Trapping and squeeze fits are not considered in this simple model. Even so, the model is far too difficult to solve optimally. Heuristics are thus under development.

6.3. *Sub-problem 3: Stack locating*

At any site, the ease of access to the structure will vary. For example, a road may lead directly to the south edge of a structure, while trees prohibit access to the north edge. It is assumed that all stacks will be dropped along the same edge of the structure, which is input by the user. The problem is then to establish where along that edge each stack should be placed. This can easily be found in order to minimise total material handling distance.

6.4. *Sub-problem 4: Stack delivery sequencing*

To construct an entire house via panels, many stacks will be necessary. It may not be physically possible to deliver all stacks together (or one right after the other), however, since drop-off locations may result in stacks that physically overlap if present at the same time. Additionally, one must ensure that the stack arrival sequence results in a feasible build process (e.g. if panels are dropped at the structure's south edge, one must start with the north construction zones). As many different stack delivery sequences will be feasible, only stack precedence constraints are established, giving the panel manufacturer flexibility in establishing the actual delivery sequence.

6.5. *Sub-problem 5: Construction task planning*

This problem consists of establishing the sequence of construction tasks needed to get each panel from its initial location/orientation to its final location/orientation in the panellised house. As described in section 4, a generic taxonomy of construction tasks has been developed. For each panel, a sequence of these generic tasks must be established, then parameterised as required (e.g. variable quantity of workers for a carrying task). Because different task types may be possible for a given action (e.g. various carrying tasks can be used to move a panel) and the selected tasks may need to be parameterised, many possible task sequences may be possible for a given panel.

One approach being explored for construction task planning is to simply employ the global objective for the overall panellisation design/construction planning problem. For example, if the global objective is to minimise ergonomic risk β, tasks that create the lowest risk are chosen and then workers assigned accordingly. This may lead to infeasibility, however. Minimising β, for example, may result in the maximum quantity of workers for all tasks, which could result in fewer panels being worked on in parallel and thus increasing the total time (and cost) required until construction cannot be completed within time/budget. Further work is under way to establish how to address this sub-problem.

6.6. *Sub-problem 6: Construction task scheduling*

The construction task scheduling problem is that of determining which construction tasks are performed when and by which worker(s). The problem closely resembles job shop scheduling, where a set of jobs must be processed on a set of machines and each job can visit different machines and in a different order. Job shop scheduling problems are notoriously difficult to solve and, despite extensive research, optimal methods are seldom available (Askin and Standridge 1993). Similarly, deterministic project scheduling for construction projects is also difficult (Ahuja and Thiruvengadam 2004). One widely used and well-studied heuristic approach for job shop scheduling is to employ dispatching rules: whenever a job is completed at a machine, a simple rule is used to select the next job to run (e.g. select the job having the shortest processing time). This same approach is employed via the use of construction rules: whenever a construction task has been completed by one or more workers, a simple rule can be used by each worker to select the next panel to work on. For example, the rule could be of the following form:

> if (tasks where an additional worker can help are available);
> and (one or more of these is $\leq$ a distance x away);
> and (one or more of these $\leq$ y% complete);
> then from the set of such tasks, select (closest task, task with lowest ergonomic risk, most time remaining, etc.);
> or else (go to the nearest panel drop-off site having one or more panels remaining).

Ergonomic and performance (i.e. task time) data are required to execute such rules and these data are available as described above. By changing one or more parameters, different construction rules are possible. Discrete simulation is then used to determine how construction proceeds and the resulting construction schedule, for given construction rules. An example of this overall approach can be seen in Mizark and Bayhan (2006), who compared the performance of dispatching rules in an actual job shop environment and provided guidance for schedulers to determine effective dispatching rules for that type of system.

6.7. *Simultaneous solution of sub-problems 5 and 6*

Analysis of the construction task identification and scheduling problems shows that they are not independent. Some tasks require a certain number of construction workers, so the number of workers available must be known. But this cannot be determined until the construction schedule is established, which in turn requires knowledge of the construction tasks. Because of this dilemma, both construction task identification and scheduling (sub-problems 5 and 6) should ideally be solved simultaneously. This approach can easily be implemented via the use of construction rules (see sub-problem 6). Such rules can be extended so that the next panel and corresponding construction task to employ are chosen together.

To implement the overall approach described above via a DSS, various software packages are required. These include applications for relational databases (so information on ergonomics exposures and risks, and performance data can be maintained), discrete simulation and discrete optimisation. These will all be integrated within a web-based application, developed using ASP.NET.

7. Discussion

Residential carpentry is a relatively high-risk occupation in terms of morbidity and mortality. Given the potential for design impact in safety (and arguably ergonomics), however, what accounts for the lack of more substantial designer involvement (Hinze and Wiegand 1992)? Several explanations are apparent from the work of Gambatese and colleagues (Gambatese *et al.* 1997, Gambatese and Hinze 1999, Hecker and Gambatese 2003). Construction designers have limited education and experience related to construction safety and comparable results have been found with regard to ergonomics (Kim *et al*. 2008). In addition, there is a pervasive attitude that construction work is inherently unsafe and that design has a minimal impact on safety. Compounding this is the traditional construction model, in which there is a strict financial and legal separation between the design process and people and the contractors/constructors. Additional barriers include the range of stakeholders involved, large numbers of often small companies (subcontractors), limited resources and limited control of workplace conditions by subcontractors (van der Molen *et al*. 2005).

Despite these barriers, enhancing construction safety through design is becoming more common, often via legislation (Lin and Mills 2001, Hecker and Gambatese 2003, Gibb 2004, Lam and Chen, 2004). In the US, there appears to be at least a willingness to implement safety in construction design (Gambatese *et al*. 2005). To capitalise on this willingness and to achieve the potential benefits of ergonomics in construction design, the barriers identified above must be overcome. One particular barrier impeding the implementation of safety in design is the lack tools or guidelines (Gambatese *et al*. 2005). Efforts to facilitate ergonomics in residential construction design are focused on the development of a DSS as described above. This tool is intended to enable designers to incorporate ergonomics issues in their design process, specifically for panellised walls.

Most residential construction is a craft-based enterprise, driven by a design, but disconnected from the actual method of assembly and its impact on the human workers. Modern residential designers are typically removed from most on-site production activity and rely heavily on a distribution of subcontractor construction and installation knowledge associated with the diverse systems that comprise a home. These subcontractors are provided with little or no guidance on acceptable construction methods associated with the design, other than material specification and schedule expectations. The lack of consideration given to the effects of panel design on the construction process or the on-site labour (O'Brien *et al*. 2002) is representative of residential construction processes in general, where fragmentation and sub-optimisation are typical.

The proposed DSS can overcome some of these barriers, but clearly not all. Several advantages, though, are inherent to the DSS. Use of the software will facilitate a more proactive approach to ergonomics in one aspect of residential construction. It also addresses the need expressed by designers for appropriate tools. By addressing ergonomics aspects early in the construction process, and facilitating input by designers, the overall impact is expected to be more efficient and effective than more reactive, site-based interventions. The DSS is scalable and can incorporate a range of additional tasks or processes involved with panellised wall construction, assuming requisite input data are available. Use of laboratory-based tasks simulations will provide quite detailed and extensive information on exposures. Such data allow for ergonomic risk assessment using a range of contemporary tools, but the DSS can also be easily adapted in the event that more advanced tools are developed. It is also suggested that a primary advantage in this approach is the inclusion of both ergonomics and productivity as basic components. Thereby, a designer (or other user) can quantify the effects of modifications on both fundamental aspects, perhaps by determining a weighting or balance between the two.

It is important to note that the proposed approach is not without cost, however. Different panel sizes and quantities may take more or less time/cost to build at the factory and changes to stacking and loading of trucks may result in additional loading effort and trips. As this upstream work is expended in the factory, however, where working conditions are controlled and modern equipment and practices employed, substantial time/cost savings in the field can be realised for relatively little time/cost in the facility. Additionally, while ergonomic risk is reduced in the field, it does not increase at the facility, as the same modern equipment and practices (designed to address ergonomics) can be used.

The DSS is a novel attempt to address a fairly difficult problem. As such, a number of limitations are involved. It is being developed with a somewhat narrow scope, that of panellised wall construction. Within this, only a subset of worker tasks are actually incorporated, specifically those that represent relatively larger physical demands (e.g. lifting, carrying, etc.). Laboratory-based measurements are necessarily also narrow in scope, in that only a subset of potential variables and levels can be tested. This results in a need to estimate exposures and associated risks for some tasks. Furthermore, for those tasks modelled, all workers are considered identical with regard to risk and performance to keep the problem manageable. Finally, the eventual usability and utility of the DSS is difficult to anticipate. While initial input from designers is being used to drive development, substantial testing and refinement will be necessary, and is planned, to accommodate a majority of end users.

Several directions for future work on and extensions to the DSS can be envisioned, primarily to address the noted limitations. In particular, model validity can be greatly improved by recognising that workers are in actuality far from identical with regard to ergonomic risk and performance. A method for incorporating this variability is needed. In addition, the underlying concepts and methods described here might be used to develop similar tools in other areas of construction, such as roofing, drywall, masonry, finish carpentry, etc. Application to other occupational sectors may also be feasible, yet it is likely that some aspects of the fundamental approach will differ. Providing such tools, however, that can address ergonomic (or safety) concerns proactively, that integrate ergonomics with other business concerns, that generate quantitative assessments and that allow for rapid simulation of alternatives can be envisioned as having a substantial benefit over a range of occupations.

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References

Ahuja, V. and Thiruvengadam, V., 2004. Project scheduling and monitoring: current research status. *Construction Innovation*, 4, 19–31.

Askin, R.G. and Standridge, C.R., 1993. *Modeling and analysis of manufacturing systems*. New York: John Wiley & Sons, Inc.

Bonauto, D., *et al*. 2006. Prioritizing industries for occupational injury and illness prevention and research, Washington State Workers' compensation claims, 1999–2003. *Journal of Occupational and Environmental Medicine*, 48, 840–851.

Bureau of Labor Statistics, 2005. *Table R4. Number of nonfatal occupational injuries and illnesses involving days away from work by industry and selected events or exposures leading to injury or illness, 2005; Construction* [online]. Available from: http://www.bls.gov/ [Accessed 18 October 2007].

Chantawit, D., *et al*. 2005. 4D CAD-Safety: visualizing project scheduling and safety planning. *Construction Innovation*, 5, 99–114.

Cholewicki, J., McGill, S.M., and Norman, R.W., 1995. Comparison of muscle forces and joint load from an optimization and EMG assisted lumbar spine model: towards development of a hybrid approach. *Journal of Biomechanics*, 28, 321–331.

Chow, D.H.K., *et al*. 2005. Postural perturbation and muscular response following sudden release during symmetric squat and stoop lifting. *Ergonomics*, 48, 591–607.

Commissaris, D.A.C.M. and Toussaint, H.M., 1997. Load knowledge affects low-back loading and control of balance in lifting tasks. *Ergonomics*, 40, 559–575.

Fadier, E. and Garza, C.D.L., 2006. Safety design: towards a new philosophy. *Safety Science*, 44, 55–73.

Forde, M.S. and Buchholz, B., 2004. Task content and physical ergonomic risk factors in construction ironwork. *International Journal of Industrial Ergonomics*, 34, 319–333.

Fredericks, T.K., *et al*. 2005. Occupational injuries and fatalities in the roofing contracting industry. *Journal of Construction Engineering and Management*, 131, 1233–1240.

Gambatese, J.S., 2000. Designing for safety. *In*: R.J. Coble, J. Hinze, and T.C. Haupt, eds. *Construction safety and health management,* chapter 8. Upper Saddle River, NJ: Prentice-Hall, 169–192.

Gambatese, J.A., Behm, M., and Hinze, J.M., 2005. Viability of designing for construction worker safety. *Journal of Construction Engineering and Management*, 131, 1029–1036.

Gambatese, J. and Hinze, J., 1999. Addressing construction worker safety in the design phase: Designing for construction worker safety. *Automation in Construction*, 8, 643–649.

Gambatese, J.A., Hinze, J.W., and Haas, C.T., 1997. Tool to design for construction worker safety. *Journal of Architectural Engineering*, 3, 32–41.

Gibb, A.G.F., 2004. Designing for safety and health in construction – A European/UK perspective. *In*: S. Hecker, J. Gambatese, and M. Weinstein, eds. *Designing for safety and health in construction*. Eugene, OR: UO Press, 44–56.

Hecker, S. and Gambatese, J.A., 2003. Safety in design: a proactive approach to construction worker safety and health. *Applied Occupational and Environmental Hygiene*, 18, 339–342.

Hignett, S. and McAtamney, L., 2000. Rapid entire body assessment (REBA). *Applied Ergonomics*, 31, 201–205.

Hinze, J.W., 1997. *Construction safety*. Upper Saddle River, NJ: Prentice Hall, Inc.

Hinze, J. and Wiegand, F., 1992. Role of designers in construction worker safety. *Journal of Construction Engineering and Management*, 118, 677–684.

Holbein, M.A. and Redfern, M.S., 1997. Functional stability limits while holding loads in various positions. *International Journal of Industrial Ergonomics*, 19, 387–395.

Hsiao, H. and Simeonov, P., 2001. Preventing falls from roofs: a critical review. *Ergonomics*, 44, 537–561.

Kim, H.N., *et al*. 2006. Risk assessment of panelized wall systems in residential construction using critical incident technique. *Proceedings of the 50th annual human factors and ergonomics conference*, 16–20 October, San Francisco, CA. Santa Monica, CA: Human Factors and Ergonomics Society, 2222–2226.

Kim, S., *et al*. 2008. Knowledge and opinions of designers of industrialized wall panels regarding incorporating ergonomics in design. *International Journal of Industrial Ergonomics*, 38, 150–157.

Kirwan, B. and Ainsworth, L.K., 1993. *A guide to task analysis*. London: Taylor & Francis.

Lam, Y.T. and Chen, Z., 2004. The development of the construction legal system in China. *Construction Management and Economics*, 22, 347–356.

Lin, J. and Mills, A., 2001. Measuring the occupational health and safety performance of construction companies in Australia. *Facilities*, 19, 131–138.

McAtamney, L. and Corlett, E.N., 1993. RULA: a survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, 24, 91–99.
Mizark, P. and Bayhan, G.M., 2006. Comparative study of dispatching rules in a real-life job shop environment. *Applied Artificial Intelligence*, 20, 585–607.
Moir, S., *et al*. 2003. Making sense of highway construction: a taxonomic framework for ergonomic exposure assessment and intervention research. *Applied Occupational and Environmental Hygiene*, 18, 256–267.
National Association of Home Builders Research Center, 2002. *Technology roadmap: Advanced panelized construction*. Washington, DC: US Department of Housing and Urban Development.
Nepal, M.P., Park, M., and Son, B., 2006. Effects of schedule pressure on construction performance. *Journal of Construction Engineering and Management*, 132, 182–188.
Nussbaum, M.A. and Chaffin, D.B., 1998. Lumbar muscle force estimation using a subject-invariant 5-parameter EMG-based model. *Journal of Biomechanics*, 37, 667–672.
O'Brien, M.J., Wakefield, R.R., and Beliveau, Y., 2000. *Industrializing the residential construction site*. Prepared for the Department of Housing and Urban Development. Washington, DC: Office of Policy Development and Research, 78.
O'Brien, M.J., Wakefield, R.R., and Beliveau, Y., 2002. *Industrializing the residential construction site – Phase III production systems*. Prepared for the Department of Housing and Urban Development. Washington, DC: Office of Policy Development and Research, 69.
Occupational Safety and Health Administration, 1990. *Analysis of construction fatalities – The OSHA data base 1985–1989*. Washington, DC: US Department of Labor.
Pertulla, P., *et al*. 2003. Accidents in materials handling at construction sites. *Construction Management and Economics*, 21, 729–736.
Ringen, K. and Stafford, E.J., 1996. Intervention research in occupational safety and health: examples from construction. *American Journal of Industrial Medicine*, 29, 314–320.
Roland, H.E. and Moriarty, B., 1990. *System safety engineering and management*, 2nd ed. New York: John Wiley & Sons.
Schneider, S. and Susi, P., 1994. Ergonomics and construction: a review of the potential hazards in new construction. *American Industrial Hygiene Association Journal*, 55, 635–649.
Shi, J.J., 2003. Simulation of real-time decision-making on resource allocation on construction sites. *Construction research congress 2003*, 19–21 March, Honolulu, Hawaii. Reston, VA: ASCE, 114–121.
Snook, S.H. and Ciriello, V.M., 1991. The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics*, 34, 1197–1213.
Staudenmann, D., *et al*. 2007. Effects of EMG processing on biomechanical models of muscle joint systems: sensitivity of trunk muscle moments, spinal forces, and stability. *Journal of Biomechanics*, 40, 900–909.
Sweeney, M.H., *et al*. 2000. Health consequences of working in construction. *In*: R.J. Coble, J. Hinze, and T.C. Haupt, eds. *Construction safety and health management,* chapter 10. Upper Saddle River, NJ: Prentice-Hall, 211–234.
van der Molen, H., *et al*. 2005. Ergonomics in building and construction: time for implementation. *Applied Ergonomics*, 36, 387–389.
Vedder, J. and Carey, E., 2005. A multi-level systems approach for the development of tools, equipment and work processes for the construction industry. *Applied Ergonomics*, 36, 471–480.
Wakefield, R.R., O'Brien, M.J., and Beliveau, Y., 2001. *Industrializing the residential construction site – Phase II information mapping*. Prepared for the Department of Housing and Urban Development. Washington, DC: Office of Policy Development and Research, 80.
Waters, T.R., *et al*. 1993. Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics*, 36, 749–776.
Weinstein, M., Gambatese, J., and Hecker, S., 2005. Can design improve construction safety? Assessing the impact of a collaborative safety-in-design process. *Journal of Construction Engineering and Management*, 131, 1125–1134.

Appendix 1: Mathematical model for panel stacking

The following integer programming model addresses the panel stacking problem in residential construction using panellised walls. Define $C_{i,r} = 1$ if panels i and r connect (i.e. contact one another) in the finished house, 0 otherwise. All $C_{i,r}$, as well as the quantity of panels N, are obtained from the panellisation plan. Also provided is the maximum panels per stack M: the quantity of stacks can then be calculated = $S = [N/M]^+$. Then define the following sets: ***Panels*** = set of panels $\{1,2,3,\ldots,N\}$, ***Stacks*** = set of stacks $\{1,2,3,\ldots,S\}$, ***Stacks1*** = set of stacks $\{1,2,3,\ldots,S-1\}$, ***Stacks2*** = set of stacks $\{2,3,4,\ldots,S-1\}$, ***Locations*** = set of panel locations $\{1,2,3,\ldots,M\}$ in a stack, ***Locations1*** = set of panel locations $\{1,2,3,\ldots,M-1\}$ in a stack, and ***Locations2*** = set of panel locations $\{2,3,4,\ldots,M\}$ in a stack. Finally, define the following variables:

$X_{i,j,k} = 1$, panel i is placed at location k in stack j; 0 otherwise. Decision variables.

$Y_{i,j,k,r,s,t} = 1$, panel i is placed at location k in stack j and panel r is placed at location t in stack s; 0 otherwise.

$R_{j,s,k} = 1$, no panels above location k, in stack j, are adjacent to the top panel in stack s ($s > j$); 0 otherwise.

$Z_{i,j,k,r,s} = 1$, panel i is placed at location k in stack j, panel r is placed on the top of stack s, and no panels above location k in stack j are adjacent to panel r; 0 otherwise.

Using the above, the panel stacking problem can be formulated as follows:

$$\text{Minimise} \sum_{k=1}^{M} \sum_{s=j+1}^{S} \sum_{j=1}^{S-1} \sum_{r=1, i\neq r}^{N} \sum_{i=1}^{N} (S-j) \cdot k \cdot C_{i,r} \cdot Z_{i,j,k,r,s}$$

subject to:

$$\sum_{k=1}^{M} \sum_{j=1}^{S} X_{i,j,k} = 1,\ i \in \textbf{\textit{Panels}} \tag{1}$$

$$\sum_{i=1}^{N} X_{i,j,k} \leq 1,\ j \in \textbf{\textit{Stacks}}, k \in \textbf{\textit{Locations}} \quad (2)$$

$$\sum_{i=1}^{N} X_{i,j,k} \geq \sum_{i=1}^{N} X_{i,j,k+1},\ j \in \textbf{\textit{Stacks}},\ k \in \textbf{\textit{Locations1}} \quad (3)$$

$$\sum_{k=1}^{t-1} \sum_{i=1}^{N} C_{i,r} Y_{i,j,k,r,j,t} \geq X_{r,j,t},\ r \in \textbf{\textit{Panels}},\ j \in \textbf{\textit{Stacks}},\ t \in \textbf{\textit{Locations2}} \quad (4)$$

$$Y_{i,j,k,r,s,t} \leq X_{i,j,k},\ i,r \in \textbf{\textit{Panels}},\ j,s \in \textbf{\textit{Stacks}},\ k,t \in \textbf{\textit{Locations}} \quad (5)$$

$$Y_{i,j,k,r,s,t} \leq X_{r,s,t},\ i,r \in \textbf{\textit{Panels}},\ j,s \in \textbf{\textit{Stacks}},\ k,t \in \textbf{\textit{Locations}} \quad (6)$$

$$Y_{i,j,k,r,s,t} \geq X_{i,j,k} + X_{r,s,t} - 1,\ i,r \in \textbf{\textit{Panels}},\ j,s \in \textbf{\textit{Stacks}},\ k,t \in \textbf{\textit{Locations}} \quad (7)$$

$$Z_{i,j,k,r,s} \leq R_{j,s,k},\ i,r \in \textbf{\textit{Panels}},\ j,s \in \textbf{\textit{Stacks}},\ k,t \in \textbf{\textit{Locations}} \quad (8)$$

$$Z_{i,j,k,r,s} \leq Y_{i,j,k,r,s,1},\ i,r \in \textbf{\textit{Panels}},\ j,s \in \textbf{\textit{Stacks}},\ k,t \in \textbf{\textit{Locations}} \quad (9)$$

$$Z_{i,j,k,r,s} \geq R_{j,s,k} + Y_{i,j,k,r,s,1} - 1,\ i,r \in \textbf{\textit{Panels}},\ j,s \in \textbf{\textit{Stacks}},\ k,t \in \textbf{\textit{Locations}} \quad (10)$$

$$R_{j,s,1} = \sum_{r=1}^{N} \sum_{i=1}^{N} C_{i,r} Y_{i,j,1,r,s,1},\ j \in \textbf{\textit{Stacks1}},\ s \in \textbf{\textit{Stacks2}},\ s > j \quad (11)$$

$$R_{j,s,k} \leq \sum_{r=1}^{N} \sum_{i=1}^{N} C_{i,r} Y_{i,j,k,r,s,1},\ j \in \textbf{\textit{Stacks1}},\ s \in \textbf{\textit{Stacks2}},\ s > j,\ k \in \textbf{\textit{Locations2}} \quad (12)$$

$$M \times R_{j,s,k} + \sum_{t=1}^{k-1} \sum_{r=1}^{N} \sum_{i=1}^{N} C_{i,r} Y_{i,j,t,r,s,1} \leq M,\ j \in \textbf{\textit{Stacks1}},\ s \in \textbf{\textit{Stacks2}}, s > j,\ k \in \textbf{\textit{Locations2}} \quad (13)$$

The objective function minimises stack start delay: the time workers must wait, once a subsequent stack arrives, before it can be started. Stack start delay is zero if the top panel in each stack connects to the top panel of every other stack (this may not always be possible). Constraint (1) ensures each panel is placed in only one stack and location, while constraint (2) ensures that each location has at most one panel. Constraint (3) ensures that panels are placed sequentially, from the top down, within each stack. Constraint (4) ensures that each panel in a stack connects with at least one panel above it in the stack. Constraints (5), (6) and (7) establish $X_{i,j,k}$ from $Y_{i,j,k,r,s,t}$, while constraints (8)–(10) establish $Z_{i,j,k,r,s}$ and constraints (11)–(13) establish $R_{j,s,k}$. Trapping and squeeze fits are not considered in this model.