

Panel Stacking, Panel Sequencing, and Stack Locating in Residential Construction: Lean Approach

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Abstract: A current trend in residential construction is the use of prefabricated wall panels. Panels are manufactured at a factory, then arranged into stacks for transporting to the construction site, where they are assembled. Current approaches to planning panelized construction are focused on stacking and transport efficiency, with little consideration given to assembly. This results in excessive panel material handling during construction, increased construction lead time, and increased risk of worker overload and/or injury. This paper proposes a lean approach to panel stacking, panel sequencing, and stack locating, where panels within each stack form a continuous structure and are erected via continuous flow. The objectives are to minimize the quantity of stacks, panel material handling distance, and the work required to position and brace panels—panel interference is ignored. Few researchers have addressed this problem: a single algorithm has been reported, and this only works for certain building shapes and may provide infeasible solutions. The proposed approach and algorithm result in improved performance, have no shape restrictions, and always provide feasible solutions. Additionally, computational experiments show that the algorithm outperforms methods being employed in the construction industry today. DOI: 10.1061/(ASCE)CO.1943-7862.0000520. © 2012 American Society of Civil Engineers.

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Introduction

Residential construction using prefabricated walls is becoming an established trend in the United States and abroad. In this approach, wall sections (panels) are fabricated at a factory, then transported to the construction site for assembly. The approach offers many advantages over traditional, “stick-built” construction. Quality is vastly improved, as panels can be fabricated in manufacturing facilities using tools, techniques, jigs, and fixtures unavailable at the construction site. Additionally, both the time to produce panels and the on-site construction time can be decreased dramatically, as can the amount of material needed. A study by the Building Systems Council (National Association of Home Builders 2009) reports that construction of a 2,600-sq-ft home with trusses and panels took just 37% of the work hours needed for a stick-built home, and also used 26% less lumber and generated 76% less waste. Panelized construction also reduces the need for skilled labor and the risk of on-site theft of materials (Shepherd 2000).

The first step in the panelized residential construction process is to come up with a *panelization plan*, which specifies how to divide the walls of a building into panels. The panel manufacturer produces the panels and arranges them into one or more *stacks* for shipment to the construction site. Upon arrival, each stack is dropped at some location on the structure floor. Workers unbind the stack, then

each panel in the stack is carried to its final location in the structure, erected (tipped upright), positioned, braced (to keep it from falling), and ultimately attached to the other panels to form a continuous structure.

An important part of the panelized approach is the initial planning stage following panelization, where the panel manufacturer must figure out what panels go into each stack and how they should be arranged. Furthermore, the stack drop-off locations on the structure floor must be determined, as must the sequence in which the workers will install the panels found in each stack. Current approaches to these problems are focused on stacking, with the objective typically being to minimize the quantity of stacks so that they can be taken to the site with the fewest trips possible. Drop-off locations are typically at the discretion of the driver of the delivery truck, with stacks dropped off at the easiest locations to get to, even though such locations may significantly increase the distance workers must move panels. Finally, little consideration is given to how construction will proceed once the stacks are delivered. The construction foreman or lead hand must determine the construction sequence for each stack, with little more to go on than the individual’s own experience. Whatever sequence is selected, the arrangement of panels in the stack invariably causes problems. Workers must routinely remove one or more panels from a stack to get to the one they want: removed panels are moved off to the side (necessitating additional material handling) or simply left on the floor (creating a safety hazard). Further material handling is incurred walking around panels left on the floor. Panels that do not connect with any completed panels, but are easily accessible in the stack, are often moved directly to their final locations and erected. Such panels, being free-standing, require substantial temporary bracing to remain upright until they can be permanently attached to other panels. In other cases, using easily accessible panels first results in problems for downstream panels when the former blocks or otherwise restricts access for the latter. Overall, the current approach to panel stacking, panel sequencing, and stack locating

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results in not only excessive construction time, but also increased safety hazards and increased risk of worker injury and overload.

This paper proposes an approach to panel stacking, panel sequencing, and stack locating aimed at addressing these problems. The approach is based upon lean manufacturing, which has revolutionized manufacturing worldwide (Womack and Jones 2003) and has more recently made inroads into the construction field (e.g., Construction Industry Institute 2005; Sharma et al. 2006; Watkins et al. 2009). To focus on maximizing performance (e.g., minimize panel material handling distance), panel interference is intentionally ignored. This refers to both *unload interference* (a panel cannot be unloaded without hitting a finished panel already in place) and *stack interference* (the stack overlaps all or part of a panel's final location in the structure). Relevant literature is reviewed first, followed by a detailed description of the problem and discussion of objectives. The proposed approach is then presented, followed by a detailed exposition of the corresponding algorithms. Computational experiments are described, and results presented and discussed. Finally, concluding remarks are provided, along with a discussion of where additional research is needed. The notation used throughout the paper is presented at the end.

Literature Review

A review of the literature has found only two items concerned with the panel-stacking, panel-sequencing, and/or stack-locating problems in residential construction using panelized walls. Shewchuk et al. (2009) present a framework for tackling the problems in a lean context. The structure floor plan is divided into a set of nonoverlapping zones, and the problems are then solved on a zone basis. This "zone approach" guarantees that unload interference does not occur, but performance (total panel move distance and quantity of stacks) suffers as a result. Guo (2010) also tackles the panel-stacking, panel-sequencing, and stack-locating problems using the zone approach. A second approach is also presented, where the problems are solved directly (no zone constraints exist). Unlike the zone approach, the focus is on maximizing performance: both unload and stack interference are ignored. The algorithm presented suffers from several shortcomings, however: it requires the edge of the structure along which the panels are dropped to be straight, and can result in infeasible solutions when installing exterior panels. Furthermore, the approach and algorithm are evaluated by approximating the stacking problem as a two-dimensional cutting stock problem, limiting the validity of the results. This paper follows this second approach (maximum performance, worry about interference later) and addresses each of these shortcomings.

In addition to these items, the most closely related papers are those dealing with layout planning, lean construction, and construction process planning. Jang et al. (2007) propose a floor-level construction material layout to minimize repositioning construction materials, using a genetic algorithm to tackle the problem. They report that their approach reduces material handling time, but they consider elements such as crane location only: panel stacking and stack locations are not addressed. Hegazy and Elbeltagi (1999) present a model and genetic algorithm for layout planning that "places facilities" at a construction site. They assume that panels are stacked when they are delivered to the construction site, and hence do not address the panel-stacking problem.

In the area of lean construction, Moosa and Abdelhamid (2005) developed a production planning model based on lean construction production planning concepts and Six Sigma techniques. It was reported that lean construction aims at identifying and eliminating

waste and that continuous improvement is needed. The issue of panel stacking, however, is not addressed. Choo et al. (1999) created a database program that implemented several lean construction techniques to help crew foreman allocate available equipment and resources. But again, the panel-stacking problem was not examined. Zhang et al. (2005) propose replacing the traditional management approach for residential construction site operation with a management philosophy that has as its sole and unifying objective the elimination of process waste. But this paper does not consider stacking at all: waste refers only to missing or broken tools/equipment, missing information, improperly staged material, and incomplete prior work.

Several authors have investigated automatic generation of construction process plans. Hu (2005) presented a model based on geometric reasoning, which reverses the disassembly process to obtain the construction process. The model provides a graph of precedence constraints, thus allowing feasible construction sequences to be established. But the related issue of how the panels should be stacked (for any given sequence) is not addressed: this is left for construction workers in the field. Nguyen and Oloufa (2001) developed a building design methodology, via a solid modeling platform, which can generate complex building information. Nguyen (2005) then proposes a framework that can generate sequences of construction activities automatically. But the framework is limited to the use of spatial information to establish construction sequences: other factors such as work spaces, panel stacking, and stack locations are not considered.

In summary, several related papers provide useful background for tackling the panel-stacking, panel-sequencing, and stack-locating problems, but only two tackle the problems directly and these have shortcomings that limit their applicability.

Problem Description

Fig. 1 shows a plan view of a hypothetical panelized structure. Throughout this paper, the writers refer to the top, bottom, left, and right side of the structure with respect to this plan view. Additionally, the writers define each panel as being either horizontal or vertical, depending upon how it appears in this view (e.g., panel 15 is horizontal, panel 18 is vertical). As shown in Fig. 2, all panels

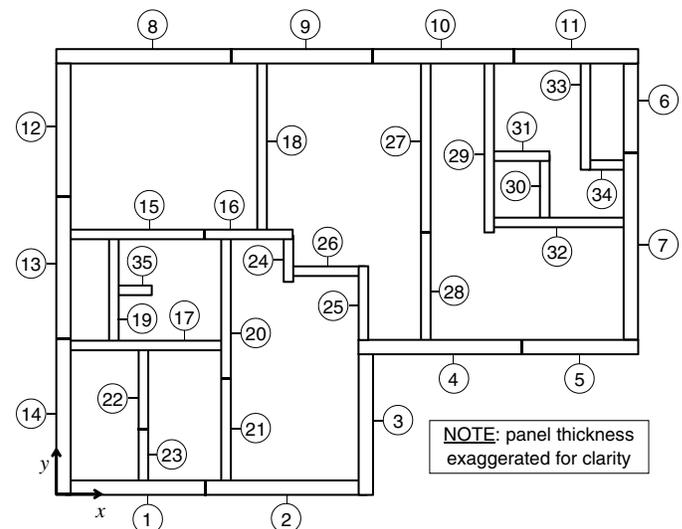


Fig. 1. Example panelized building structure (35 panels)

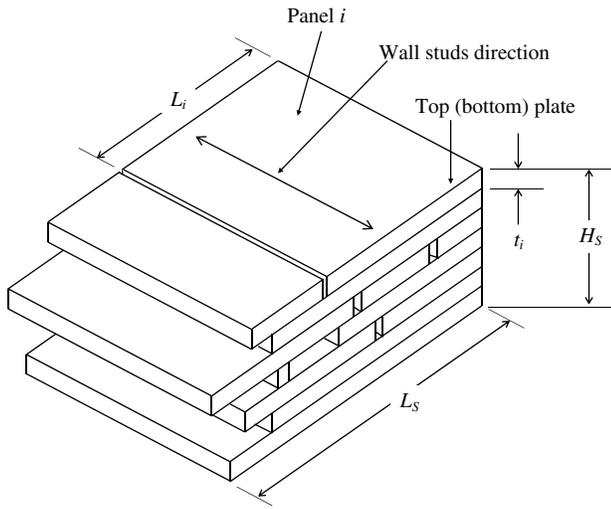


Fig. 2. Example stack for panelized residential construction

within each stack are similarly oriented (all wall studs run in the same direction in the stack) and are of the same height. Although stacks may vary in height and length, there will be some maximum stack height beyond which workers cannot safely remove panels and the stacks themselves become unstable. Additionally, there will be some maximum stack length beyond which the stack cannot be easily transported and also becomes too big to work with. Stacks are dropped off sequentially, with each placed directly on the sub-floor of (as opposed to being placed beside) the structure. This is necessary for workers to safely move each panel from a stack to a location within the structure. Finally, all stacks are dropped off with their length dimension (bottom plate, top plate) parallel to and one length edge flush with some edge of the structure, and the stack sides cannot overlap the structure edges. Each of these assumptions reflects current practice, as verified through discussion with panel manufacturers and/or observations of actual panelized wall construction.

Given a panelization plan, maximum stack length, and maximum stack height, the objective is to find (1) what panels go into each stack and how they are arranged into layers, (2) the construction sequence for the panels in each stack, and (3) stack drop-off locations.

Objectives

As previously discussed, the current emphasis in residential panelized construction is on efficient stack formation at the factory and minimizing the quantity of trips to the job site. One obvious objective is thus to minimize the quantity of stacks, as this results in the fewest trips (all other factors being equal). The high prevalence of occupational injuries sustained by workers in panelized construction, however, points to the need to factor ergonomic considerations into the design process. Along these lines, the writers propose three additional objectives aimed at making the process both more efficient and safer for the workers.

The first of these is to minimize the total effort needed for workers to carry the panels from stacks to final locations in the structure. While this depends upon worker path preferences, move methods, obstacles, and other factors unknown at this stage of planning, it first and foremost depends upon the rectilinear distance from the panel's starting location (stack centroid) to its final location in the structure. Additionally, the fact that larger panels will be more

difficult to move, due to both increased size (making navigation and clearing obstacles more difficult) and weight, cannot be ignored. For simplicity, panel length is used as a multiplier to account for this fact. Thus, *total weighted panel material handling distance (WMH)*, is calculated as follows:

$$WMH = \sum_{k=1}^M \sum_{i \in S_k} L_i \cdot (|x_i - u_k| + |y_i - v_k|) \quad (1)$$

The second objective is to minimize the work needed to position each panel (jog, slide, or other fine movement) at its final location once it has been erected. Although this depends upon positioning methods, tools available, etc., it first and foremost depends upon how well the panels "fit together" during construction. Figs. 3(a and b) show examples of good and bad panel fit scenarios: in the latter case, panel *i* must be squeezed between multiple panels. The work required to position panel *i* is minimized when a good fit scenario exists: each such panel *i* exhibits *fittability*. An overall measure of fittability is

$$FIT = \sum_{i=1}^N f_i / (N - Q) \quad (2)$$

where f_i = fittability of panel $i = 1$ if the panel encounters a good panel fit scenario, 0 otherwise; Q = quantity of panels that can never exhibit fittability (last exterior panel or last interior panel of any wall spanning exterior panels, e.g., panel 27 or 28, Fig. 1).

The third objective is to minimize the work required to brace each panel following positioning, so that it remains upright. Again, this depends upon several factors not established at this stage, but at the most basic level the work is minimized when panel *i* connects to (joins with) one or more panels already in place. The panel can then be directly fastened to the other panel(s) with minimal bracing: substantial additional bracing may be required otherwise. Each such panel *i* exhibits *connectivity*. Noting that the first panel installed can never exhibit connectivity, an overall measure of connectivity is

$$CONN = \sum_{k=1}^M \sum_{i \in S_k} c_i / (N - 1) \quad (3)$$

where c_i = connectivity of panel $i = 1, |conn_i \cap (S_1 + S_2 + \dots + S_{k-1} + \{s_{k[1]}, s_{k[2]}, \dots, s_{k[n-1]}\})| > 0, 0$ otherwise; $s_{k[j]} = j^{th}$ panel in sequence S_k , and $n = j | s_{k[j]} = i |$.

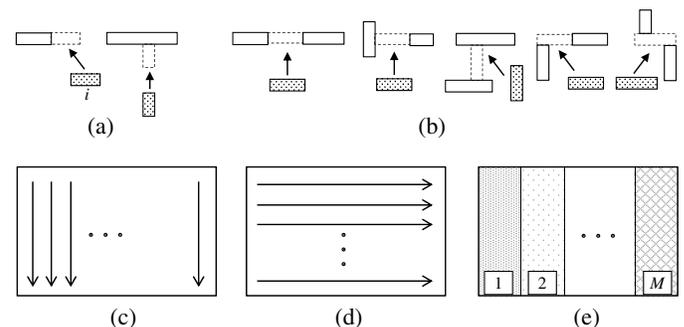


Fig. 3. (a) Good panel fit scenarios; (b) bad panel fit scenarios; (c) top-to-bottom build pattern; (d) left-to-right build pattern; (e) stack arrivals, panels resulting in vertical "stack areas"

Approach

The proposed approach to panel stacking, panel sequencing, and stack locating is based upon the following lean concepts and principles (Monden 2012):

1. Panels are always taken in the order in which they appear in the stack. In other words, the top panel of each stack (or one of the panels on the top layer, if multiple panels are present) is always the next one needed. Workers no longer slide panel after panel off to the side, onto the floor, etc., 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 not only accelerates construction, it also eliminates the safety hazards resulting from panels left lying on the ground, tipped against walls, etc.
2. Once a panel is removed from a stack, it is processed in one continuous operation until it is fixed at its final position in the structure (lean principle: continuous flow).
3. Panels must be installed quickly and correctly the first time (lean principle: jidoka).

The proposed approach is as follows. Stacks are dropped off along a single edge of the structure: this is referred to as the *dropping edge*. At least one edge must be accessible for stack drop-off: using one edge only allows the delivery procedure to be simplified and standardized. To simplify the algorithm, the bottom edge (e.g., panels 1–5 in Fig. 1) is always taken as the dropping edge. The overall panel construction sequence is established first: each exterior panel must be put in place before any of its connecting interior panels. Additionally, construction progresses both left–right (by convention) and top–bottom (so that the stack area is kept clear as long as possible). The use of these two preferred *construction directions* ensures connectivity and fittability are maximized, which makes it possible to install panels quickly and correctly the first time.

The preferred construction directions can be achieved in two different ways: by building top-to-bottom [Fig. 3(c)] or left-to-right [Fig. 3(d)]. The writers refer to each of these as a *build pattern*. Top-to-bottom is used to assign panels to stacks: this results in stacks whose panels more or less fill a series of vertical “stack areas,” starting with the left edge of the structure and progressing to the right edge [Fig. 3(e)]. This tight clustering of panels around each stack keeps material handling distances small. Left-to-right is then used to sequence the panels in each stack; this delays the top–bottom movement (and thus preserves stack accessibility) as long as possible. To ensure that the panels in each stack can be used in the order provided, whatever the sequence, each stack is allowed to consist of both exterior and interior panels. Furthermore, panels of different thickness (e.g., 6-in. thick exterior panel versus 4-in. thick interior panel) are allowed to be located in the same stack layer; spacers can be used to ensure the layers remain parallel in such cases. This allows exterior and interior panels to share the same layer, maximizing space utilization in the stack and minimizing stack quantity. Finally, it is assumed that only one stack is on the structure at a time. This allows drop-off locations to overlap, if necessary, allowing the best possible location to be established for each.

Note that the previously mentioned approach considers a single dropping edge and set of preferred construction directions (left–right, top–bottom). In practice, the approach should be tried with each accessible dropping edge, as well as the other preferred construction directions. Different dropping edges can be obtained by simply rotating the panelization plan. Additionally, (1) a right–left construction direction can be obtained by mirroring the panelization plan about the central vertical axis, and (2) a bottom–top

construction direction can similarly be obtained by mirroring about the central horizontal axis.

Algorithm

The previously described approach is realized via an iterative algorithm consisting of six stages (Fig. 4). Procedures for each of these stages are described in detail in the following sections. To aid in understanding the algorithm, an example problem will be solved. This consists of the structure of Fig. 1 ($t_i = 6$ in. for exterior panels, 4 in. for interior panels) and $H_{S,max} = 60$ in., $L_{S,max} = 135$ in.

Stage 1: Panel Precedence Constraints

Though there are many possible ways to construct a panelized structure (and hence many sets of feasible precedence constraints), a single set of constraints is possible given that (1) each exterior panel must be put in place before any of its interior connecting panels, (2) all panels (except the first) exhibit connectivity, and (3) the given build pattern is followed, unless this violates (2). Exterior panels are handled separately from interior panels: the two procedures are as follows.

1. Exterior Panel Precedence Constraints

To establish exterior panel precedence constraints, the first exterior panel *FP* and last exterior panel *LP* are first identified. Using a left-to-right build pattern, these are the top-left corner panel and bottom-right corner panel, respectively. Starting with *FP*, one moves clockwise around the exterior to *LP*, recording precedence for each pair of panels. The process is then repeated, but moving

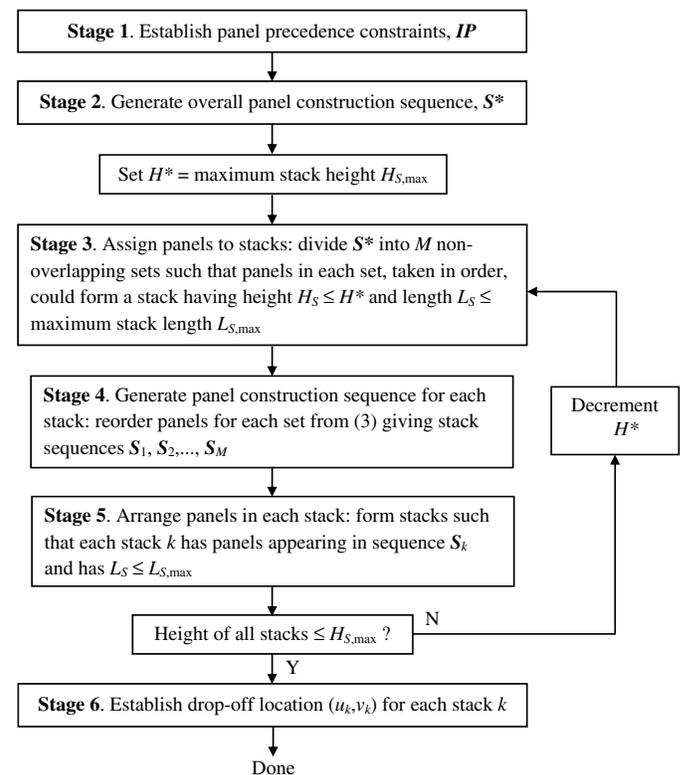


Fig. 4. Overall approach to panel stacking, panel sequencing, and stack locating

counterclockwise. For the example structure (Fig. 1), $FP = 8$ and $LP = 5$ (throughout this paper, bold font is used to denote exterior panels and regular font denotes interior panels). Clockwise rotation from FP results in $IP = \{(8, 9), (9, 10), (10, 11), (11, 6), (6, 7), (7, 5)\}$. Counterclockwise rotation then results in $IP = \{(8, 12), (12, 13), (13, 14), (14, 1), (1, 2), (2, 3), (3, 4), (4, 5)\}$.

2. Interior Panel Precedence Constraints

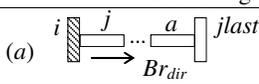
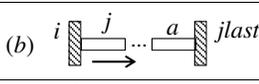
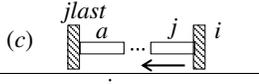
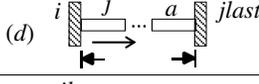
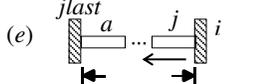
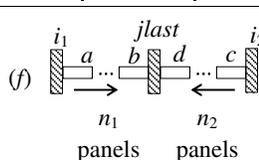
Interior precedence constraints are formed by recursively constructing branches, again using a left-to-right build pattern, and setting precedence constraints one branch at a time. The procedure is detailed as follows: the function $LtoR(F)$ sorts the panels in set F following a left-to-right build pattern.

0. Initialize. Set $F =$ set of exterior panels $= \{i \in 1, \dots, N \mid b_i = 1\}$. Then sort these panels: $F^* = LtoR(F)$. Mark all exterior panels as assigned and interior panels as unassigned, and set $T =$ temporary storage array $= \{\}$, $m = 1$.
1. Let $i = m^{th}$ panel in F^* . Find the set of panels that connect with panel i but currently have no precedence relationship with this panel $= B = \{j \in conn_i \mid (i, j) \notin IP, (j, i) \notin IP\}$. If $|B| = 0$, go to step 4; otherwise, find $B^* = LtoR(B)$, set $n = 1$.
2. Construct the branch starting with root panel i and having first branching panel j , where $j = n^{th}$ panel in B^* . Branching is illustrated in Fig. 5: each branch continues in the direction of panel j and ends with panel j_{last} , which is either an unassigned (and hence terminal) panel [Fig. 5(a)] or an already-assigned

panel [Fig. 5(b)]. Precedence relationships are then established for each successive pair of panels moving in the branch direction, the set of unassigned panels is stored as $bpanels$, and each of these unassigned panels is then assigned. In the event that the last panel in the branch is already assigned, four special cases are possible, depending upon the branch direction and how the first and last panels are constrained in the structure. These cases are shown in Figs. 5(c–f).

3. Add branch panels to $T: T \leftarrow T + bpanels$; add precedence constraints to IP . If $n < |B^*|$, more branches remain for root panel i . Set $n \leftarrow n + 1$ and go to step 2.
4. If $m < |F^*|$ more root panels remain for current panel set F^* . Set $m \leftarrow m + 1$ and go to step 1.
5. All branches have been formed for all root panels in the current panel set F^* . If $|T| > 0$, form the next set of root panels: set $F^* = LtoR(T)$. Then set $T = \{\}$, $m = 1$, and go to step 1. Otherwise, the procedure is done.

Fig. 6 shows the application of the previously mentioned algorithm to the example problem. Examples of branching scenario (a) from Fig. 5 are branches $9 \rightarrow (18) \rightarrow (16)$ and $14 \rightarrow (17) \rightarrow (20)$; branching scenario (b) can be seen via $7 \rightarrow (32) \rightarrow 29$ and $13 \rightarrow (15) \rightarrow 16$. An example of special case (c) is provided by branch $25 \leftarrow (26) \leftarrow 24$: the branch direction is reversed. Branch $32 \rightarrow (30) \rightarrow 31$ also satisfies special case (c); reversing this branch results in a cycle ($29 \rightarrow 31 \rightarrow (30) \rightarrow 32 \rightarrow 29$), however, so the branch direction is reversed back. Branch $10 \rightarrow (27) \rightarrow (28) \leftarrow 4$ is an example of special case (d): a squeeze fit is needed

Branching scenario ¹	Result ²	Branch construction ³
(a)  $A_{jlast} = 0, Br_{dir} = P_{dir}$	Standard branch	$i \rightarrow [j] \rightarrow \dots \rightarrow [a] \rightarrow (jlast)$
(b)  $A_{jlast} = 1, Br_{dir} = P_{dir}$	Standard branch	$i \rightarrow [j] \rightarrow \dots \rightarrow [a] \rightarrow jlast$
(c)  $A_{jlast} = 1, Br_{dir} \neq P_{dir}$	Reverse Br_{dir}	$i \leftarrow [j] \leftarrow \dots \leftarrow [a] \leftarrow jlast$
(d)  $A_{jlast} = 1, Br_{dir} = P_{dir}$, panels i and $jlast$ both constrained	Squeeze fit 2 nd last panel in branch (= a)	$i \rightarrow [j] \rightarrow \dots \rightarrow [a] \leftarrow jlast$
(e)  $A_{jlast} = 1, Br_{dir} \neq P_{dir}$, panels i and $jlast$ both constrained	Reverse Br_{dir} , squeeze fit panel j	$i \rightarrow [j] \leftarrow \dots \leftarrow [a] \leftarrow jlast$
(f)  $jlast$ part of two branches, 'sandwich panel' results: $n_1 = n_2 = 1$ $n_1 > 1$ $n_1 = 1$	Fix panelization plan Squeeze fit panel b	$i_1 \rightarrow [a] \rightarrow \dots \rightarrow [b] \leftarrow jlast$ $i_2 \rightarrow [c] \rightarrow \dots \rightarrow [d] \rightarrow jlast$
	Reverse #2 Br_{dir} , squeeze fit panel c	$i_1 \rightarrow [a] \rightarrow \dots \rightarrow [b] \rightarrow jlast$ $i_2 \rightarrow [c] \leftarrow \dots \leftarrow [d] \leftarrow jlast$

¹ Each scenario shown is representative of many possible cases. Any joint type (T, butt, corner) is possible between panels: the branches can also be vertical. $A_n = 1$ if panel n already assigned, 0 otherwise; $Br_{dir} =$ branching direction, $P_{dir} =$ preferred build direction.

² Whenever branching direction reversed, reverse back if cycling occurs.

³ n : panel n already assigned, $[n]$: panel n may or may not be already assigned, (n) : panel n not assigned.

Fig. 5. Branching scenarios

<i>i</i>	<i>B</i>	<i>B</i>*	<i>n</i>	branch ¹	<i>bpanels</i>	precedence constraints added
Step 0: <i>F</i> = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14}						
<i>F</i>* = {8, 9, 10, 11, 12, 6, 7, 13, 14, 4, 5, 3, 1, 2}, <i>T</i> = { }						
9	{18}	{28}	1	9 →(18)→(16)	{18,16}	(9,18), (18,16)
10	{27,29}	{27,29}	1	10 →(27)→(28)← 4	{27,28}	(10,27), (27,28), (4,28)
			2	10 →(29)	{29}	(10,29)
11	{33}	{33}	1	11 →(33)	{33}	(11,33)
7	{32,34}	{34,32}	1	7 →(34)→33	{34}	(7,34), (34,33)
			2	7 →(32)→29	{32}	(7,32), (32,29)
13	{15}	{15}	1	13 →(15)→16	{15}	(13,15), (15,16)
14	{17}	{17}	1	14 →(17)→(20)	{17,20}	(14,17), (17,20)
4	{25}	{25}	1	4 →(25)	{25}	(4,25)
1	{23}	{23}	1	1 →(23)→(22)→17	{23,22}	(1,23), (23,22), (22,17)
2	{21}	{21}	1	2 →(21)←20←16	{21}	(2,21), (20,21), (16,20)
Step 5: <i>T</i> = {18, 16, 27, 28, 29, 33, 34, 32, 15, 17, 20, 25, 23, 22, 21}						
<i>F</i>* = {18, 27, 29, 33, 34, 32, 15, 16, 28, 20, 25, 17, 22, 21, 23}, <i>T</i> = { }						
29	{31}	{31}	1	29→(31)	{31}	(29,31)
32	{30}	{30}	1	32→(30)→31 (c)	{30}	(32,30), (30,31)
15	{19}	{19}	1	15→(19)→17	{19}	(15,19), (19,17)
				1 →(23)→(22)→17 becomes 1 →(23)←(22)←17; (23,22) becomes (22,23) (22,17) becomes (17,22) (f)		
16	{24}	{24}	1	16→(24)	{24}	(16,24)
25	{26}	{26}	1	25←(26)←24 (c)	{26}	(26,25), (24,26)
Step 5: <i>T</i> = {31, 30, 19, 24, 26}						
<i>F</i>* = {31, 30, 19, 24, 26}, <i>T</i> = { }						
19	{35}	{35}	1	19→(35)	{35}	(19,35)
Step 5: <i>T</i> = {35}						
<i>F</i>* = {35}						
-						

¹*n*: panel *n* already assigned, (*n*): panel *n* not assigned.

Fig. 6. Interior panel precedence constraints algorithm applied to example problem (bold = exterior panels)

for panel 28. An example of special case (e) is provided by branch **2** → (21) ← (20) ← **16**. Finally, branches **1** → (23) → (22) → (17) and 15 → (19) → 17 satisfy special case (f); the former thus becomes **1** → (23) ← (22) ← (17).

The previous two algorithms result in a total of 45 panel precedence constraints for the example problem. These are shown in the precedence diagram of Fig. 7.

Stage 2: Overall Panel Construction Sequence

The overall panel construction sequence is generated by repeatedly forming the set of panels that are not yet assigned but have all of their predecessors assigned, then selecting a panel from this set. Vertical exterior panels are given priority, so that whenever a vertical wall is started, all panels in the wall are put up in uninterrupted sequence. This aids in enclosing the working space as quickly as possible. When no vertical exterior panels are present, the goal is to select panels using a top-to-bottom build pattern, so that any subset of panels in the overall sequence will result in a vertical stack area as previously described [Fig. 3(e)]. Horizontal panels connected at their right edge to vertical exterior panels must be handled separately, however, as these must be built right-left (because the exterior panel must come first). The procedure is shown in detail in the following steps: the function *T*to*B* (*F*) sorts the panels in set *F* following a top-to-bottom build pattern.

0. Initialize. Set *S** = overall panel construction sequence = {*FP*}.

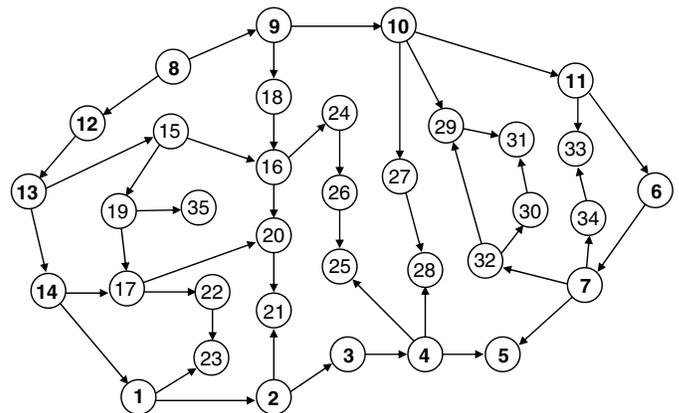


Fig. 7. Precedence diagram generated for example problem (bold = exterior panels)

1. Determine the initial set of candidate panels for the next assignment = $C = \{j | j \notin S^*, I \in S^* \forall (i, j) \in IP\}$.
2. Find the subset of *C* having vertical exterior panels only = $V = \{j | j \in C, b_j = d_j = 1\}$. Note that there can be at most one such panel, due to precedence constraints.
3. If $|V| = 1$, set $m = \text{first panel in } V = V_{[1]}$; go to step 6.
4. Find the subset of *C* consisting of horizontal interior panels that have their right edge connecting to an exterior

panel = $H = \{j | j \in C, b_j = 0, b_k = 1 \forall k \in conn_{j,R}\}$. If $\sum_{i \in C} (1 - b_i) = |H|$, select from H the panel having the maximum y -coordinate: $m = \arg \max_j \{y_{edge_j}, j \in H\}$; go to step 6.

- Sort the panels in C using a top-to-bottom build pattern: $C^* = TtoB(C)$. Then take the first panel from this set: $m = c_{[1]}^*$, where $c_{[k]}^* = k^{th}$ panel in C^* .
- Add panel m to the sequence: $S^* \leftarrow S^* + m$. If $|S^*| = N$, the procedure is done; otherwise, go to step 1.

Application of the previously described procedure to the example problem results in the following. After selection of the first panel ($m = 8$), $C = \{9, 12\}$ and $V = \{12\}$, giving $m = 12$. Vertical exterior panels 13 and 14, interior panel 15, and horizontal exterior panel 1 are similarly selected. At this point, it is found that $C = \{2, 9, 19\}$, $C^* = \{19, 2, 9\}$, and $m = 19$. Panels continue to be selected via V or C^* until the 29th panel, where $C = \{5, 32, 34\}$, $H = \{32, 34\}$, and $m = 34$. Panel selection then continues via C^* only until the last panel, $m = 33$. The resulting panel construction sequence is $S^* = (8, 12, 13, 14, 15, 1, 19, 17, 35, 22, 23, 2, 3, 9, 18, 16, 20, 21, 24, 26, 4, 25, 10, 27, 28, 11, 6, 7, 34, 32, 29, 5, 30, 31, 33)$.

Stage 3: Assignment of Panels to Stacks

Panels are assigned to stacks by dividing S^* into a succession of nonoverlapping sets. Each set of panels then constitutes a stack. If the panels in each stack were then erected in order, connectivity would be guaranteed and vertical stack areas [Fig. 3(e)] would be obtained. In such a case, the only constraint in establishing the sets is that the resulting stacks each have height $H_S \leq H^*$ and length $L_S \leq L_{S,max}$, where H^* = current maximum stack height $\leq H_{S,max}$ (Fig. 4).

There are many ways in which S^* can be divided into stacks while meeting the maximum height and length criteria. To minimize the quantity of stacks, however, a simple greedy approach can be used. Panels are taken from S^* , one at a time and in order. The first panel starts the top layer of the first stack. An attempt is made to add each successive panel to the same layer of the same stack. Whenever this results in $L_S \leq L_{S,max}$, a new layer (below the current one) is started. The height of each layer is that of the thickest panel in that layer. Whenever starting a new layer would result in $H_S > H^*$, a new stack is started. This procedure continues until all panels from S^* have been assigned; the result is M stacks, with stack k having panel set P_k and $P_1 \cup P_2 \cup \dots \cup P_M = P^*$, where P^* = set of all panels in S^* .

Assigning panels to stacks in this manner for the example problem results in $M = 3$ stacks, with $P_1 = \{8, 12, 13, 14, 15, 1, 19, (17, 35), (22, 23), 2, 3\}$, $P_2 = \{9, 18, 16, 20, (21, 24), 26, 4, 25, 10, 27, 28, 11\}$, and $P_3 = \{6, 7, (34, 32), 29, (5, 30), (31, 33)\}$.

Stage 4: Construction Sequence, Panels in Each Stack

As previously mentioned, the stacks formed in stage 3 both guarantee connectivity and result in vertical stack areas when the panels are taken in the order provided. At this point, however, the build pattern for each stack is top-to-bottom, while left-to-right is preferred. Thus, the construction sequence for the panels in each stack is recalculated, assuming a left-to-right build pattern. The procedure is essentially the same as that used for the entire structure (stage 2), except that a left-to-right build pattern is used for step 5. Applying the procedure to the example problem results in $S_1 = (8, 12, 13, 14, 15, 19, 35, 17, 22, 1, 23, 2, 3)$, $S_2 = (9, 10, 11, 18, 27, 16, 20, 24, 26, 4, 28, 25, 21)$, and $S_3 = (6, 7, 34, 33, 32, 29, 30, 31, 5)$.

Stage 5: Stack Arrangements

The procedure for forming stacks is similar to that used in panel assignment (stage 3). For each stack k , panels are taken from S_k , one at a time and in order. The first panel starts the top layer of the stack k . An attempt is made to add each successive panel to the same layer of the stack. Whenever $L_{S,max}$ is exceeded, a new layer (below the current one) is started. This procedure continues until all panels from S_k have been assigned. Note that as the set of panels forming the stack is fixed, $H_{S,max}$ can be exceeded. In this case, iteration is employed to reduce the quantity of panels in each stack until all stacks are of acceptable height (Fig. 4).

Assigning panels to stacks in the previously described manner for the example problem results in $P_1 = \{8, 12, 13, 14, 15, (19, 35), 17, 22, 1, 23, 2, 3\}$, $P_2 = \{9, 10, 11, 18, 27, 16, (20, 24), 26, 4, (28, 25), 21\}$, and $P_3 = \{6, 7, (34, 33), 32, 29, (30, 31), 5\}$. Stack heights are 62, 52, and 34 in., respectively. The first stack now exceeds $H_{S,max}$, so it is necessary to iterate as shown in Fig. 4 (a single iteration only is used here for brevity):

- Stage 3 is repeated using $H^* = 56$ in., giving $P_1 = \{8, 12, 13, 14, 15, 1, 19, (17, 35), (22, 23), 2\}$, $P_2 = \{3, 9, 18, 16, 20, (21, 24), 26, 4, 25, 10, 27, 28\}$, and $P_3 = \{11, 6, 7, (34, 32), 29, (5, 30), (31, 33)\}$.
- Stage 4 is then repeated, giving $S_1 = (8, 12, 13, 14, 15, 19, 35, 17, 22, 1, 23, 2)$, $S_2 = (3, 9, 10, 18, 27, 16, 20, 24, 26, 4, 28, 25, 21)$, and $S_3 = (11, 6, 7, 34, 33, 32, 29, 30, 31, 5)$.
- Finally, stage 5 is repeated, giving $P_1 = \{8, 12, 13, 14, 15, (19, 35), 17, 22, 1, 23, 2\}$, $P_2 = \{3, 9, 10, 18, 27, 16, (20, 24), 26, 4, (28, 25), 21\}$, and $P_3 = \{11, 6, 7, (34, 33), 32, 29, (30, 31), 5\}$; stack heights are 56, 52, and 40 in. All stacks are now within $H_{S,max}$, so this solution is acceptable.

Stage 6: Stack Drop-Off Locations

As previously described, all stacks are dropped off along the same edge of the structure and cannot overlap the structure edges. Furthermore, all stacks have one length edge flush with the dropping edge. This results in a single area for each stack, within which that stack must be completely contained. If a discrete x -direction step size (say, 1 inch) is then assumed, a finite set of drop-off locations for each stack can be calculated. The optimal location for a stack

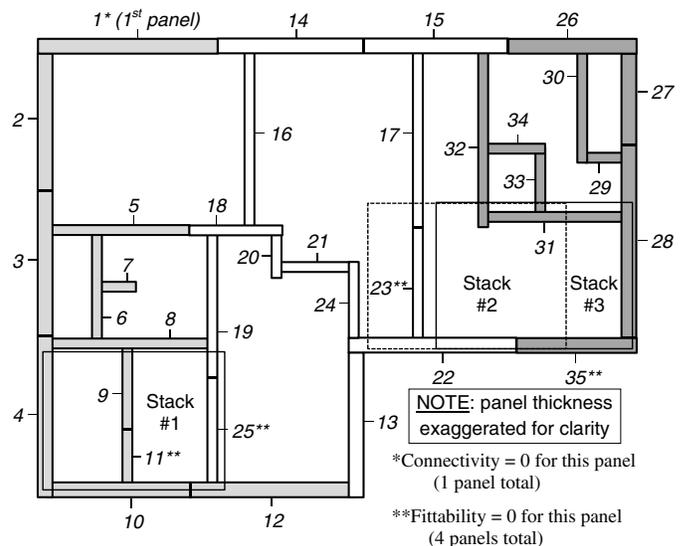


Fig. 8. Overall solution for example problem

(for the given step size) can then easily be found by simply examining all drop-off locations and selecting the one that minimizes the weighted panel move distance.

Fig. 8 shows the overall solution for the example problem (panels in each stack, panel sequence, and stack drop-off locations).

Computational Experiments

Experimental Design

A set of computational experiments were conducted to establish the performance of the proposed approach to panel stacking, panel sequencing, and stack locating in panelized residential construction. Three sizes of residential single-story home designs were investigated—small (<1,500 sq ft), medium (1,500–3,000 sq ft), and large (>3,000 sq ft). For each scenario, five home plans were randomly chosen from an online database of housing plans (The Home Plan Group 2009), giving 15 problems. For each problem, the structure was panelized using a preferred panel length of 10 ft (8–12 ft is common in practice). Panel lengths were adjusted as required to account for door and window openings, with a maximum panel length of 12 ft observed. All 15 panelization plans can be found in Appendix D of Guo (2010). Maximum stack height and stack length were 60 in. (5 ft) and 150 in. (12 1/2 ft), respectively; these are typical values found in practice.

For each problem, the stacks, construction sequence, and stack locations were found using three different approaches: manual solution, commercial software, and the proposed algorithm. A professional panel designer, with eight years of experience generating panel stacks for residential construction, provided manual solutions for all problems. Solutions were also generated with a widely used, commercially available wall panel design and stacking software package. For both the manual and commercial software approaches, the standard practice of separate exterior and interior panel stacks was employed; the resulting stacks for all problems can be found in Appendix D of Guo (2010). Field observations over many structures, and discussions with panel manufacturers, indicate that the methods used by the panel designer and commercial software are representative of those used throughout the industry today.

In both the manual and commercial software approaches, the only result generated is the set of stacks. Neither the actual sequence in which the panels in each stack are to be used nor the stack drop-off locations are provided. Regarding the panel sequence, it is assumed that the panels in each stack are used in stack order, as they are with the proposed algorithm. For multipanel stack layers, the best possible sequence is determined for the panels as follows. The order in which the panels are presented, left-to-right in the stack, is taken as the initial sequence. This is checked and adjusted as necessary to obtain maximum connectivity. If no adjustment is needed, it is checked and adjusted to obtain maximum fittability. When workers in the field use panels in stack order, the results thus show directly the problems they would encounter with connectivity and fittability. When workers do not take panels in the order provided (but instead move panels off to the side, onto the floor, etc., to get a panel that “works better,” i.e., has better connectivity and/or flexibility), the results can be taken as an indicator of the amount of work they need to do in moving such panels. It is important to keep in mind, however, that in such a case the workers will not likely know the best selections to make and as such may move a lot of panels and still encounter connectivity/fittability problems. Thus, the results likely overestimate the true connectivity/fittability in such cases. For determining stack drop-off locations in the manual and computerized approaches, the same optimal procedure is used as is employed in the proposed approach (step 6).

The proposed algorithm was coded in C++ using Visual Studio 2010, and run on a 2.8-GHz laptop. To aid in program debugging and verification, a separate program for drawing the panelization plan, then drawing the stacks at their drop-off locations and animating the sequence in which the panels from each stack are placed, was developed using C++ and Proof 3D animation software (Wolverine Software Corp.).

Results

Experimental results are presented in Tables 1 and 2. For each case and solution approach, the four performance measures [quantity of stacks (M), total weighted panel material handling distance (WMH), connectivity (CONN), and fittability (FIT)] are presented. An additional measure, total panel material handling distance (MH)

Table 1. Computational Results for Proposed Algorithm versus Existing Approaches

Case	N	Panel designer					Commercial software					Proposed algorithm				
		M	MH (ft)	WMH (sq ft)	CONN (%)	FIT (%)	M	MH (ft)	WMH (sq ft)	CONN (%)	FIT (%)	M	MH (ft)	WMH (sq ft)	CONN (%)	FIT (%)
S-1	23	3	472	3,524	86	82	3	447	3,527	77	64	2	384	3,038	100	100
S-2	23	3	337	2,655	77	76	3	389	3,024	82	71	2	327	2,554	100	100
S-3	27	3	421	3,230	85	88	3	473	3,525	85	88	2	415	3,107	100	100
S-4	25	3	484	3,748	88	83	3	520	4,107	88	79	2	419	3,368	100	100
S-5	33	4	619	4,576	78	78	4	644	4,827	88	84	3	563	4,058	100	100
M-1	46	5	1,391	10,977	82	84	5	1,347	10,681	87	80	4	1,296	10,305	100	100
M-2	51	6	1,447	11,515	90	82	5	1,476	11,514	90	90	4	1,266	10,073	100	100
M-3	49	6	1,245	9,498	83	83	4	1,260	9,629	90	79	4	1,272	9,371	100	100
M-4	64	8	1,572	13,355	81	74	6	1,654	14,154	86	81	5	1,354	11,494	100	100
M-5	59	7	1,381	11,155	86	79	5	1,585	12,670	88	85	5	1,425	11,403	100	100
L-1	90	11	3,549	29,293	81	80	8	3,618	29,930	81	81	7	3,200	26,822	100	99
L-2	91	10	3,244	28,613	84	80	8	3,599	31,819	83	80	7	2,910	25,487	100	100
L-3	93	11	2,996	26,195	79	81	8	3,343	29,468	89	81	8	2,792	24,350	100	100
L-4	87	10	3,170	27,572	83	79	8	3,641	31,475	81	84	7	2,511	22,106	100	100
L-5	84	10	3,691	33,479	78	77	8	3,731	33,621	87	82	7	3,496	31,669	100	100

Table 2. Percentage Improvement Obtained Using Proposed Approach versus Existing Approaches

Case	N	Improvement over panel designer					Improvement over commercial software				
		M	MH	WMH	CONN	FIT	M	MH	WMH	CONN	FIT
S-1	23	33	19	14	16	22	33	14	14	30	56
S-2	23	33	3	4	30	32	33	16	16	22	41
S-3	27	33	1	4	18	14	33	12	12	18	14
S-4	25	33	13	10	14	20	33	19	18	14	27
S-5	33	25	9	11	28	28	25	13	16	14	19
M-1	46	20	7	6	22	19	20	4	4	15	25
M-2	51	33	13	13	11	22	20	14	13	11	11
M-3	49	33	-2	1	20	20	0	-1	3	11	27
M-4	64	38	14	14	23	35	17	18	19	16	23
M-5	59	29	-3	-2	16	27	0	10	10	14	18
L-1	90	36	10	8	23	24	13	12	10	23	22
L-2	91	30	10	11	19	25	13	19	20	20	25
L-3	93	27	7	7	27	23	0	16	17	12	23
L-4	87	30	21	20	20	27	13	31	30	23	19
L-5	84	30	5	5	28	30	13	6	6	15	22

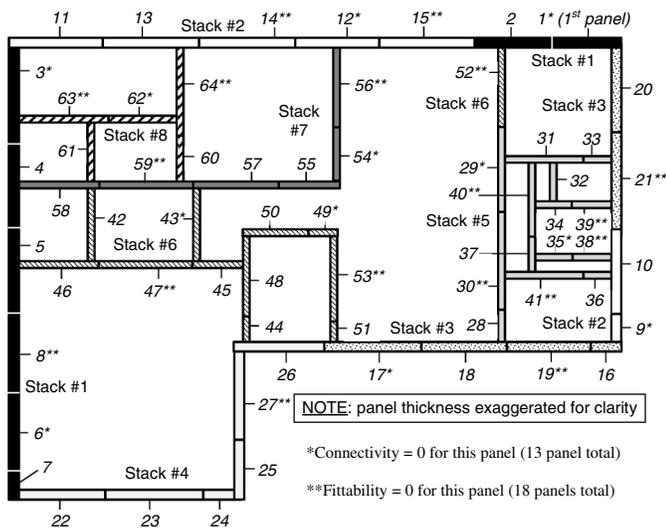


Fig. 9. Case M-4 (64 panels), as solved by the panel designer

is also provided to get a feel for the actual distances traveled by workers. Table 1 shows the actual values for the performance measures, while Table 2 shows the percentage improvement in each measure using the proposed approach. To aid in understanding the results, the panel stacking and sequencing solutions for case M-4 are shown in Figs. 9 (manual approach) and 10 (proposed approach). These figures also indicate panels for which connectivity or fittability was not achieved.

Performance of the proposed algorithm, as compared with both existing approaches, is as follows:

- The quantity of stacks (*M*) was reduced in all cases compared with the manual approach, and in 12 of 15 as compared with the commercial software approach. In no cases did the proposed approach result in a greater quantity of stacks.
- Total panel material handling distance (MH), as compared with the manual approach, decreased for 13 of the 15 cases. The improvement ranged from 1%–21% (average = 8%): for the two nonimproving cases (M-3 and M-5), the proposed approach was

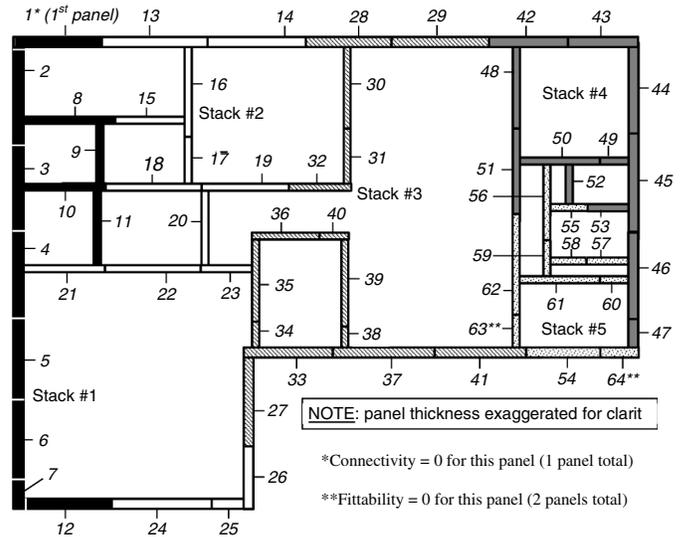


Fig. 10. Case M-4 (64 panels), as solved by the proposed algorithm

worse by only 2% and 3%, respectively. Compared with the commercial software approach, total panel move distance decreased for 14 of the 15 cases, with the improvement ranging from 4%–31% (average = 14%) and performance worse by only 1% for the sole nonimproving case (M-3). In terms of actual values, the improvement of 31% for case L-4 represents a reduction in material handling distance of 659 ft: the workers are carrying panels for approximately 1/8 mile less using the proposed approach.

- Total weighted panel material handling distance (WMH), as compared with the manual approach, decreased for all cases but one with improvement ranging from 1%–20%. The sole nonimproving case (M-5) exhibited a performance decrease of 2%. Compared with the commercial software approach, WMH decreased in every case, with the improvement ranging from 3%–30%. The average improvement over the manual and commercial software approaches was 8% and 14%, respectively, the same values found for MH.
- Connectivity (CONN) was improved in all cases. While the proposed approach guarantees 100% connectivity, the manual approach provided at most 90% connectivity (M-2) and an average value of 83%. The commercial software approach was very similar, with a maximum of 90% connectivity (M-2, M-3) and an average of 85%. The percentage improvement in connectivity using the proposed approach ranged from 11%–30% over all cases, with an average 21% improvement over the manual approach and 17% over the commercial software approach. Considering case M-4, the manual approach results in 13 panels having zero connectivity (Fig. 9); each of these panels is free-standing and requires substantial bracing upon installation. With the proposed approach (Fig. 10), only the first panel has zero connectivity (this cannot be avoided).
- Fittability (FIT) was improved in all cases. Both the manual and commercial software approaches had an average fittability of approximately 80%; the maximum value observed was 90% (M-2). Fittability with the proposed approach was 100% in all cases except L-1, where it was 99%. This provided improvement ranging from 11%–56% over all cases, with an average 25% improvement over both the manual and commercial software approaches. Again considering case M-4, the manual approach results in 18 panels having zero fittability: each of these panels must be squeezed into place between already-completed

panels. The proposed approach (Fig. 10) results in only two panels having zero fittability, both of which are unavoidable.

In terms of solution speed, the algorithm solved each problem in less than 1 s.

Discussion of Results

The computational results indicate that the proposed approach to panel stacking, panel sequencing, and stack locating appears to be a significant improvement over existing methods. The proposed algorithm dominated both the manual and commercial software approaches for 13 of the 15 cases: M, MH, WMH, CONN, and FIT were all improved upon. In the remaining two cases (M-3, M-5), only MH and/or WMH were worse, and then just slightly (1%–3%). Considering all cases and both existing methods, on average the proposed approach results in the following:

- A total of 25% fewer stacks to deliver;
- An 11% reduction in the total distance (and weighted total distance) the workers need to walk while carrying panels;
- The elimination of all unavoidable free-standing panels, and thus the additional work required to brace such panels (this represents a 20% reduction in such panels encountered using existing methods); and
- The elimination of all unavoidable squeeze fits except one (in case L-1), and thus the additional work (and aggravation) required to position such panels (this represents a 25% reduction in such panels encountered using existing methods).

While the magnitude of reduction in MH and WMH may not seem too impressive in isolation, it becomes more significant when the quantity of stacks is considered. In general, as M increases, MH (WMH) decreases: in the limit, each panel has its own stack and there is no x -distance move component at all. Conversely, as M decreases, one would expect MH (WMH) to increase. The proposed algorithm dramatically decreases M , but despite this MH (WMH) decreases as well. The decrease in M can be partially explained by the fact that with both existing approaches, each stack can consist of either exterior or interior panels only; this can result in spare capacity in the last external stack that cannot be used. But this does not account for the entire decrease in M : the proposed algorithm itself comes into play and avoids trading off material handling distance for stack quantity as would be expected.

The 20% and 25% average reduction in CONN and FIT, respectively, is extremely important. The writers' field observations, over many structures from several different construction firms, have repeatedly shown instances of free-standing panels (following the first panel) being erected, as well as workers struggling to force-fit panels that require a squeeze fit (often hammering the panel into place as a last resort). The proposed approach eliminates the first problem and minimizes the second. This will have a substantial impact on how field crews work, as well as the safety and efficiency with which positioning and bracing are performed.

It should also be kept in mind, when comparing performance, that the panel designer and commercial software do not generate full solutions and the present study has determined the best possible values for the missing items. The writers' field observations and discussions with panel manufacturers and construction crews, however, indicate that the best values are seldom realized in practice. Thus, performance of the current methods has likely been overestimated by a substantial margin.

Conclusions

In this paper, an approach and algorithm for solving the panel-stacking, panel-sequencing, and stack-locating problems in

residential panelized construction were presented. The focus was on maximizing performance: panel interference was ignored, being left for a later stage in the design process. Performance was investigated by experiments comparing the algorithm with solutions generated manually (experienced panel designer) and via commercially available software for 15 cases. The results indicate that the proposed approach can improve the process considerably, simultaneously reducing the quantity of stacks, the distance workers must walk carrying panels, the bracing needed to erect panels, and the additional work needed to position panels when squeeze-fit scenarios are encountered. Reducing the quantity of stacks has always been an objective for the panel maker, to minimize the quantity of trips to the job site. The goal of this paper was to develop methods for solving the aforementioned problems that also make the job safer and more efficient for the workers. The approach and algorithm presented satisfy this goal, without compromising the original objective of minimizing stack quantity. It should also be noted that the algorithm works with any building shape and always provides feasible solutions, issues encountered with the only other reported algorithm that tackles the problems ignoring panel interference (Guo 2010).

Several issues, however, remain to be explored. In terms of the algorithm, alternatives need to be explored for stage 3 (dividing the overall construction sequence into stacks). A simple greedy approach was used in this paper, with each stack filled as much as possible. While this minimizes the quantity of stacks, it can also result in large move distances for some panels. Unless the last stack is full, panels can be distributed among the stacks differently (e.g., balance the panels over the stacks) without affecting stack quantity; a different solution may have a lower MH (WMH). In terms of the experiments, the effect of alternative panelization strategies needs to be explored. This paper assumed a single preferred panel length of 10 ft. In practice, it is possible to employ a smaller preferred panel length (each panel smaller, but more of them) or a larger length (each panel bigger, but fewer to worry about). Further improvement in M and MH (WMH) may be possible if the panelization strategy is taken into account for a given structure.

In terms of model validity, two items need to be addressed. First and foremost are the issues of unload interference and stack interference. When either of these occurs, panels must be moved temporarily (something the writers have been trying hard to avoid) or drop-off locations must be adjusted, or some combination of the two (or something else) is needed. Methods are needed to cope with both unload and stack interference; efforts are underway to develop a postprocessing algorithm that "adjusts" solutions as required to eliminate interference. The second item to address concerns the underlying assumption of one stack in process at a time. Although construction occurs in this manner in many instances, there are other times when multiple stacks are worked on at the same time to speed up the process. In such cases, the panel sequence can no longer be solved for each stack in isolation, as panels from different stacks can intermix during construction. Additional work is needed to tackle this difficult problem.

Finally, the proposed algorithm solves what panels go into each layer of each stack (and the sequence they are to be taken in), but not the panel location in each layer. Both performance and validity could be improved by determining such locations: MH and WMH would then be based upon the actual panel locations in the stack, rather than stack centroids. In a similar manner, it is known that either the top or bottom plate is flush with the dropping edge for each stack: a more sophisticated algorithm would calculate this orientation of each panel in the stack. This is an important design variable: workers have repeatedly been seen in the field removing

panels from stacks and finding it necessary to rotate the panels 180° (xy plane) prior to erecting them. As panel orientation does not impact any of the existing performance measures, another suitable measure would need to be developed.

A final issue to be addressed is the potential impact of the proposed approach on the factory, as it requires panels to be stacked differently (exterior and interior panels in the same stack, different panel thicknesses allowed in the same layer). Preliminary discussions with panel manufacturers have indicated that this is not expected to cause any major difficulties. In fact, this change to the way stacks are made is actually desirable: it will allow the factory to move toward lean panel production, making them just in time for each stack as opposed to batching (all exterior stacks, then all interior stacks). It will also allow for a single, standardized set of methods, tools, etc., for stacking, stack packaging, transport, etc., as only one kind of stack is then used as opposed to exterior stacks (few panels, each big and heavy, few layers) and interior stacks (many panels, each relatively light, many layers). Thus, the proposed approach not only brings lean to the construction site, it moves it upstream to the panel manufacturer as well.

Acknowledgments

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Notation

The following symbols are used in this paper:

- b_i = 1, panel i is an exterior panel; 0 *o/w* (interior);
- $conn_i$ = set of panels connecting with panel i ;
- $conn_{iR}$ = set of panels connecting with panel i via panel's right edge;
- d_i = 1, panel i oriented vertically; 0 *o/w* (horizontal);
- FP = first exterior panel in overall panel construction sequence;
- $H_{S,max}$ = maximum stack height;
- IP = set of panel precedence constraints = $\{(i, j) | \text{panel } i \text{ must precede panel } j\}$;
- L_i = length of panel i (see Fig. 2);
- $L_{S,max}$ = maximum stack length;
- LP = last exterior panel in overall panel construction sequence;
- M = quantity of stacks;
- N = quantity of panels;
- P_k = set of panels comprising stack k and their arrangement into layers, $\{(\text{panels in top layer}), (\text{panels in 2nd layer}), \dots, (\text{panels in bottom layer})\}$;
- S_k = construction sequence, panels in stack k ;
- S^* = overall panel construction sequence (all panels);
- t_i = thickness of panel i (see Fig. 2);
- (u_k, v_k) = (x, y) coordinates of stack k 's drop-off location (centroid), panelization plan;

- (x_i, y_i) = (x, y) coordinates of panel i (centroid) in the panelization plan; and
- $yedge_i$ = y -coordinate of panel i 's top edge, panelization plan.

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