Simulation Modeling and Ergonomic Assessment of Complex Multiworker Physical Processes

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***Abstract*—Discrete simulation of complex multiworker physical processes, for ergonomic and/or performance analysis, is still relatively undeveloped. Existing approaches typically have taken either a classical simulation view of the problem (focus on activities, resources, and queues: workers treated as machines) or an analytical ergonomics perspective (detailed human modeling and ergonomic assessment for well-defined limited tasks). This paper presents a new way to tackle such problems, based upon elements of both of these approaches. Novel methods are described for modeling complex multiworker physical processes within a traditional discrete-event simulation environment. These methods result in a high-level language for generating activity-based process models quickly and easily, based upon simplified activity representations. Laboratory experiments are used to derive equations that can then be used to generate ergonomic assessments (i.e., relative injury risks) for the most influential activities. By implementing these equations using data generated from a simulation run, estimates of ergonomic consequences can be obtained. To illustrate the approach, it is applied to the panelized residential housing construction process, where multiple workers build houses by moving and installing large heavy prefabricated wall panels. The example illustrates the steps presented and feasibility of the approach.**

***Index Terms*—Computer simulation, ergonomics, job design .**

I. Introduction

MANY systems employ complex manual physical processing, where items must be moved and manipulated by multiple workers, and multiple items can be in process at the same time. Of considerable concern in such systems is the extent to which workers are exposed to substantial physical demands and the associated level of musculoskeletal injury risks. To ensure that the risks to each worker are acceptable, the process must be carefully designed. Additionally, it is usually important to be able to determine how well the system performs with respect to some common metric such as throughput or cycle time.

Because process interactions, dependencies, and worker (and possibly other resource) constraints can all occur, simulation is the only viable alternative for modeling and analyzing such systems [1]. Two broad approaches exist for incorporating humans in simulations:

1) *Process-oriented simulation:* Simulations based on traditional modeling constructs (activities, resources, queues, etc.) and workers being treated as machines. Human activities and interactions are hard to model and ergonomic measures difficult to establish.
2) *Human-focused simulations:* Simulations where humans are modeled in detail (using anthropometric data) and advanced tools are used to estimate ergonomic exposures/risks for well-defined activities (e.g., lift task). This approach is not well suited to complex systems where a great variety of tasks are possible and/or multiple workers can be performing multiple tasks simultaneously.

In this paper, we propose an alternative approach to simulation modeling and ergonomic assessment of complex multiworker physical processes. The idea is essentially to combine elements of both current approaches: develop discrete simulation models and methods that represent complex human tasks and interactions with sufficient validity and, then, use advanced methods to assess ergonomic exposure/risk based upon activity data generated during simulation. The approach ultimately results in a simulator for problems within a specified domain. The simulator can provide detailed ergonomic results, for use during the design process, for any number of similar problems.

Fig. 1. Example of panelized residential construction.

To help explain and demonstrate the approach, it is applied to the panelized residential construction process (see Fig. 1). This is a form of building construction where houses are built

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from prefabricated walls (panels) made in a factory, rather than "stick-built" on-site from piles of lumber. Panels are arranged into stacks and the stacks trucked to the job site and dropped off on the structure subfloor. The construction process consists of each panel being unloaded from its stack, moved, and erected at its final location/orientation in the structure. The panels can be very large (2.44 m high × 4.88 m long) and heavy (over 113 kg). Processing is typically entirely manual, using one to four workers for each panel, and physical demands and injury risks are substantial [2], [3]. The overall construction process can be very complex: multiple panels can be in process at the same time, a fixed construction crew results in worker constraints, and the work space is constantly changing (becoming smaller) as construction proceeds. Simulation is thus the only viable approach for modeling this process in detail. Given the increasing use of panelized residential construction, a simulator developed as outlined above has substantial potential to help reduce worker risk and injuries. Efforts are currently underway to develop such a tool [4], [5].

Simulation modeling and ergonomic assessment of this process is difficult, however, as there are no set components or systems: a standard panel size does not exist and houses can take any size and shape. This results in an almost limitless variety of possible panels to move and move objectives (i.e., panel's final location/orientation with respect to its starting stack location/orientation). Thus, the set of construction activities needed to cover all possibilities is extremely large. Additionally, there are many different ways to perform a given construction activity and many different parameters to consider, e.g., panel size and weight, whether a panel is sheathed (thin protective and/or insulating layer on one face) or not, and site conditions. Panelized residential construction is thus considered to be an excellent test bed for the proposed approach to simulation modeling and ergonomic assessment of complex multiworker physical processes.

II. LITERATURE REVIEW

Process-oriented discrete simulation has been widely used for detecting sources of risk during system design. The use of such models can eliminate the need for physical scale models during the initial design stage even for complex products, such as aircraft [6]. For systems incorporating humans, however, adequate attention is not paid in modeling human behavior [7]. The literature on process-oriented simulations involving humans can be broadly categorized into the following.

1) *Those that consider humans as machines:* The focus of such simulations is not humans, but workstations and/or processes [8]. Early attempts to address worker behavior in manufacturing environments modeled group work behavior for throughput analysis by changing operating mode or worker qualifications [9]. As humans are modeled as machines, ergonomic issues are never considered in such studies.
2) *Those that consider humans in more detail:* The objective of these simulation models is modeling human behavior without considering the details of the tasks/physical activities that each individual is performing. Freudenberg and Herper [10] differentiated worker-integrated simulations from worker-oriented simulations: the logistic system is evaluated in the former, and the factors influencing the workers are analyzed in the latter. They discussed an approach for worker-oriented simulation by considering specification of individual workers in the simulation model. Mason *et al.* [11] discussed a simulation approach to incorporate varying worker activity times in the context of a manufacturing system design. For developing complex simulation of human interactions, researchers often use autonomous agent-based models (e.g., [12]): attributes used for individual agents can be work experience, qualification, competence level, etc. None of these studies consider ergonomic issues, however.
3) *Those that look at detailed ergonomic modeling:* The purpose of such models is evaluation and prediction of human factors in work processes. Wang and Verriest [13], for example, presented a geometric inverse kinematic algorithm to predict reach postures: the human arm was modeled as a four-degree-of-freedom kinematic linkage system in this study. The effects of fatigue and rotation schedules on unmanned vehicle control performance were examined using simulation in [14]. Imai *et al.* [15] showed an ergonomic simulation model of factory workers that considered human body structure, work motions, and work semantics. An ergonomic performance evaluation of an automobile disassembly system using simulation was presented in [16]. Schaub *et al.* [17] discussed commercially available products for ergonomic analysis via simulation. More recently, Perez *et al.* [18] provided a discrete-event simulation approach for comparing ergonomic impacts (fatigue prediction) of alternative assembly line designs. In these and related studies, simulation is typically performed at the workstation level, with the focus on human–machine interaction rather than worker interactions. Additionally, they consider well-structured controlled work environments where activity variations are limited.

Overall, the use of discrete simulation as a proactive ergonomic tool has been limited to relatively controlled work environments. Managers in charge of system design are still skeptical whether simulation modeling of human behavior is even feasible [6].

In occupational ergonomic studies, human-focused simulation plays a vital role. These studies often aim to investigate how the neuromuscular and musculoskeletal systems coordinate to produce movement [19]. In such cases, system analysis is typically done by collecting data from human subjects (workers), using subjective and objective methods. All of these studies, however, focus on workstation-level assessment without considering the overall system-level impact on the workers [18]. Focusing only on the workstation level eliminates the need to model interaction/coordination of multiple workers, which are more complex in nature than modeling individual workers. Digital human modeling (DHM), the computerized representation of the human body and its interaction with the environment [20], is also available via commercial software tools such as 3-D Static Strength Prediction Program [21]. Chaffin *et al.* [22] presented a novel approach to human motion simulation, where real human motion samples are stored in a database, retrieved during simulation, and then modified as necessary to match the actual scenario as closely as possible. This work is perhaps the closest to the proposed research in terms of the goal of linking simulated processes and actual ergonomic data, but again focuses on individual workers. Overall, DHM is promising for proactive ergonomic analysis, but the validity of posture/motion prediction is often limited to relatively simple movement circumstances [23] and the approach is not aimed at multiple humans working together.

Finally, the literature shows a gap in the research between simulation of collaborative processes and teamwork performance [24]. Task network modeling (task analysis) is a viable approach for modeling human behaviors via simulation in which the function performed is decomposed into different subfunctions that consist of several tasks [25]. These tasks are then modeled independently in the simulation, reducing simulation complexity. This approach was used in [26], for example, to simulate foot behaviors during manual material handling tasks. No previous studies, to our knowledge, have considered task analysis for simulation modeling involving coordination between multiple workers. In the following sections, we describe in detail how we extended the task analysis approach to model complex physical activities that require multiple workers.

III. MODELING FRAMEWORK AND APPROACH

A physical process is taken to mean a sequence of manual activities required to move/manipulate a particular item (or batch of items acting as one) from one location/orientation to another. We are concerned here with gross physical movements (i.e., material handling) only, not fine detailed movements (e.g., manual assembly). One or more workers (humans) are required to perform the physical process: the workers are seized at the start of the process and released at the process' end (if an individual is needed for only a portion of the process, the process is subdivided so the rule still applies). Workers are modeled in low fidelity and as rigid bodies: we are interested in the movement and location/orientation of workers in 2-D space (*xy* plane) only. Note that this does not mean ergonomic aspects related to postures, motions, joint loads, etc., are not considered, but rather only that this level of detail is not modeled directly in the simulation (the mechanisms by which these issues are incorporated are explained shortly). In complex physical processes employing multiple workers, there will be a large and varied set of loads imposed on the workers. As it is infeasible to identify and model every one of these loads, only those which are considered the most substantial (i.e., high-risk exposures) are isolated for detailed ergonomic analysis. These are referred to as ergonomic tasks.

The overall approach to simulation modeling and ergonomic assessment of complex multiworker physical processes is illustrated in Fig. 2. As previously outlined, a simulator is developed for the given problem domain: the ergonomic tasks associated with the process are represented within the simulator. For any simulation run, the simulator outputs time-phased data ("motion script") indicating which ergonomic tasks were performed when, with which item(s) and worker(s), and relevant location/orientation data in each case. A second software program ("ergonomics assessment engine") then reads and processes this data to provide detailed ergonomic results for that particular simulation run.

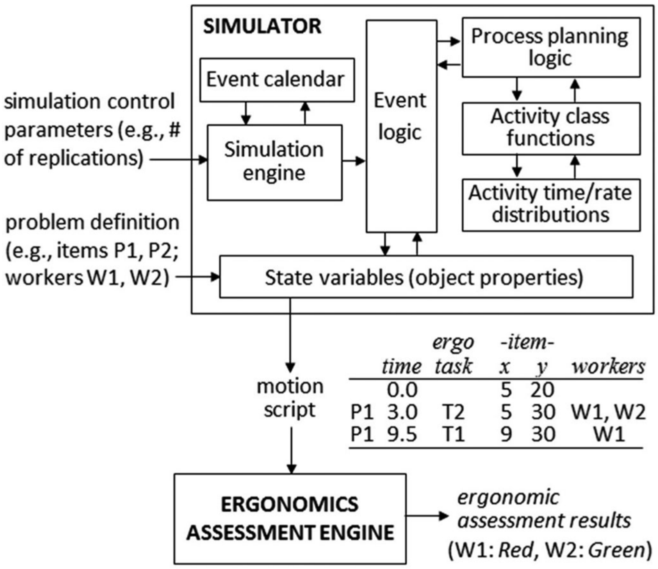


Fig. 2. Overall approach to simulation modeling and ergonomic assessment of complex multiworker physical processes.

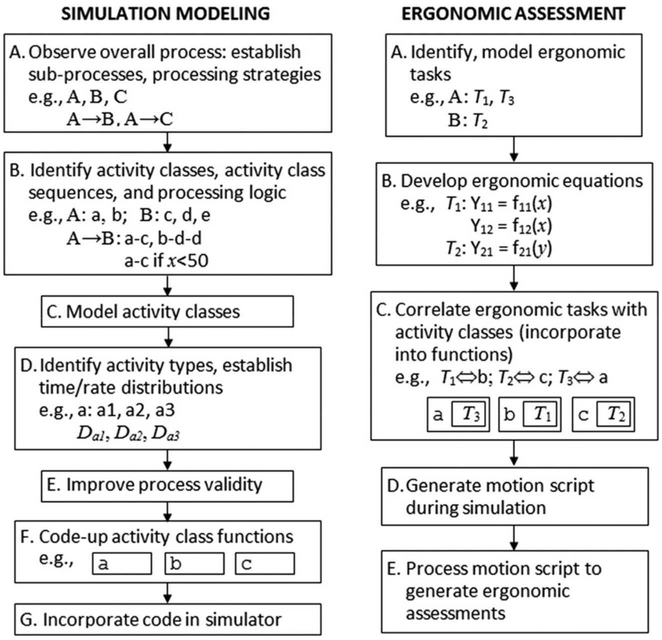


Fig. 3. Steps involved in simulation modeling and ergonomic assessment of complex multiworker physical processes.

The simulation modeling and ergonomic assessment steps involved in the above approach are illustrated in Fig. 3. On the simulation side, the first step is to identify the various subprocesses and processing strategies used. Further analysis then leads to the identification of activity classes (generic representations of how similar activities are performed), activity class sequences (how such classes can be combined to represent processing strategies), and processing logic (conditions under which each

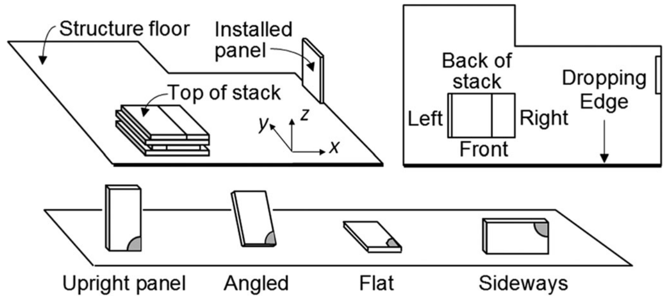


Fig. 4. Terminology used for modeling and simulation of the panelized residential construction process.

combination occurs). The activity classes are then modeled in low fidelity and hierarchically (where possible) to ensure that the resulting task-based representations are highly tractable. To establish activity durations during simulation, activity classes must be further divided into activity types and a time or rate distribution determined for each (via observation of the real process, lab-based experiments, etc.). Additional activities are then introduced to improve process validity (e.g., account for momentary worker pauses), following which the activity class functions and process planning logic can be coded-up and incorporated into the simulator.

On the ergonomics side, the ergonomic tasks associated with the subprocesses are first identified, following which one or more ergonomic equations are established for each task. Ergonomic tasks are then correlated with activities: the activity class functions in the simulator are modified such that ergonomic task data are properly captured and recording during simulation. The ergonomic equations themselves are coded directly into the ergonomics assessment engine. Simulation then results in the generation of ergonomic task data (motion script), while post-processing (ergonomics assessment engine) provides the final assessment results.

IV. SIMULATION MODELING METHODOLOGY

A. Identify Subprocesses and Processing Strategies

The first step in simulation modeling of complex multiworker physical processes is to observe the process at a high level in order to get an overall idea of what is occurring, i.e., the kinds of items being moved, objectives, process boundaries, and ways in which workers are involved. At this level, one often finds that various processing strategies can be employed. Each of these, in turn, can be articulated by a sequence of subprocesses: a given subprocess may be common across multiple processing strategies.

Panelized residential construction example: Fig. 4 shows the terminology used in the panelized residential construction process. Two processing strategies were identified:

1) *Direct panel install:* The panel is unloaded from its stack, moved to a point near its final location in the structure, and tipped upright. It is then installed (manipulated into its final location/orientation), fixed (permanently attached to other connecting panels at that location), and braced (temporary bracing applied, as needed, to ensure panel remains stationary and rigid).
2) *Indirect panel install:* The panel is unloaded from its stack and, then, moved to an area for temporary storage (leaned against a finished wall). When processing is ready to resume, the panel is retrieved, moved to the install location, and then installed, fixed, and braced as before.

Based upon the above, six subprocesses were identified: *UNLOAD*, *MOVE*, *STORE*, *RETRIEVE*, *INSTALL*, and *FIX/BRACE*. Direct panel install can then be expressed as *UNLOAD→MOVE→INSTALL→FIX/BRACE*; indirect panel install as *UNLOAD→MOVE→STORE→RETRIEVE→MOVE →INSTALL→FIX/BRACE*. The remainder of this paper will consider the direct panel install processing strategy only.

B. Identify Activity Classes, Activity Class Sequences, and Processing Logic

There can be many different ways for workers to implement a given subprocess. For example, a worker moving an item from A to B may choose to carry the item in front of his/her body, alongside, or over the shoulder. Each different way to perform a subprocess is referred to as an activity class. A processing strategy (sequence of subprocesses) can then be articulated at a more detailed level by specifying the activity class(es) for each subprocess: these are referred to as activity class sequences.

Activity classes and activity class sequences are established simultaneously by observing the processing strategy in action for various items, conditions, etc. It is also important at this step to establish the conditions under which each activity class sequence is used (process planning logic): this information will be used to perform process planning during simulation.

Panelized residential construction example: A total of 37 activity classes and 11 activity class sequences were identified via rigorous analysis of video recordings of panelized residential construction over multiple houses and by multiple contractors. Twenty-four of the activity classes are shown in Table I, along with representative illustrations (simulation animation snapshots) for 11 of these in Fig. 5. Four activity class sequences are shown in Fig. 6. The first of these is where a single worker unloads the panel from its stack using U1_5 (last panel in stack) or U5. The worker then lifts the upright panel up at his/her side (L1_1), turns to get ready to walk (RW), and then carries the panel via a series of translations or rotations (C1_1) in the *xy* plane. Once the worker arrives at the install point, he/she lowers the upright panel to the floor (D1_1), turns/repositions to get ready to install the panel (RW), then installs the panel (INSTALL), followed by panel fixing/bracing (FIX_BRC). This method was observed to be used for small panel distances (8 m or less).

C. Model Activity Classes

Activity classes can be modeled in different ways, depending upon the nature of the activities they represent. Simple activities, for example, are often straightforward to model via a sequence of tasks. This may be difficult for complex activities, however: alternative methods may be required. Additionally, it is helpful

TABLE I
EXAMPLE ACTIVITY CLASSES FOR PANELIZED RESIDENTIAL CONSTRUCTION

Activity Class	Description
UNLOAD subprocess	
U1_5	Single-worker panel unload (no helper) from floor (stack gone). Worker tips panel lying flat on floor to upright position.
U3	Flat panel unload (two to four workers). Pull top panel off of stack from stack's back, left or right side, raise/lower to C3 position.
U4	Flat panel unload following rotation (two to four workers). Rotate top panel 90° cw (ccw), pull off of stack, raise/lower to C3 position.
U5	Tip unload (one to four workers). Pull top panel off of stack (back, front, left or right side) until panel tips, bottom plate hits floor. Continue rotating panel to upright position (C5) resting on floor.
MOVE subprocess	
C1_1	Single-worker upright panel carry, panel at workers side.
C1_3	Single-worker sideways panel carry, panel at worker's side.
C3	Flat panel carry (two to four workers).
C4	Upright panel carry (two to four workers).
C5	Upright panel slide on floor (two to four workers).
L1_1	Lift upright panel at worker's side, on floor, to C1_1 position.
L1_3	Lift sideways panel at worker's side, on floor, to C1_3 position.
Lf	Lift flat panel, on floor, to C3 position (two to four workers).
Lu	Lift upright panel, on floor, to C5 position (two to four workers).
D1_1	Lower upright panel at worker's side (C1_1 position) to floor.
D1_2	Lower upright panel in front of worker (C1_2 position) to floor.
D1_3	Lower sideways panel at worker's side (C1_3 position) to floor.
Du	Lower upright panel, at C4 position, to floor (two to four workers).
RP1_2	Single-worker rotate upright panel, on floor, until sideways.
TIP	Flat panel tip (two to four workers). Lower bottom plate of panel in C3 position down to contact floor, reposition worker(s).
E1_3	Single-worker panel erect: sideways panel on floor, rotate panel about one corner until upright.
ERECT	Panel erect (two to four workers). Raise rear end of panel having bottom plate on floor until panel upright.
RW	Rotate worker in *xy* plane.
INSTALL subprocess	
INSTALL	Slide, jog and position upright panel, resting on floor, into final location/orientation in structure (one to four workers).
FIX/BRACE subprocess	
FIX_BRC	Fix, brace installed panel (one to four workers).

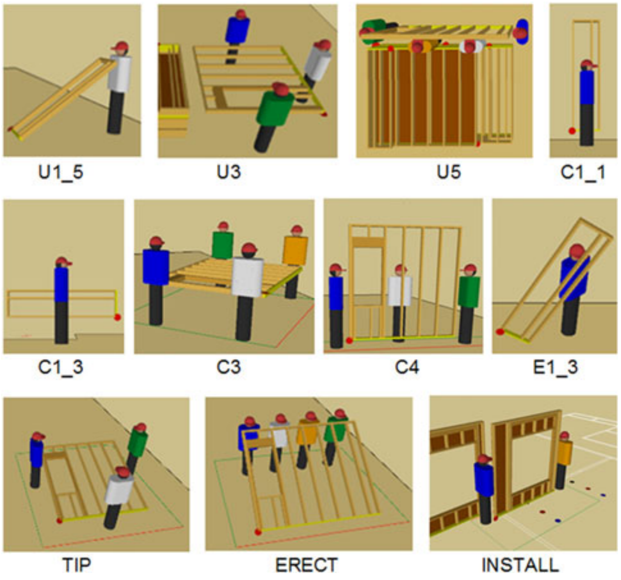


Fig. 5. Examples of activity classes (simulation animation snapshots) for panelized residential construction.

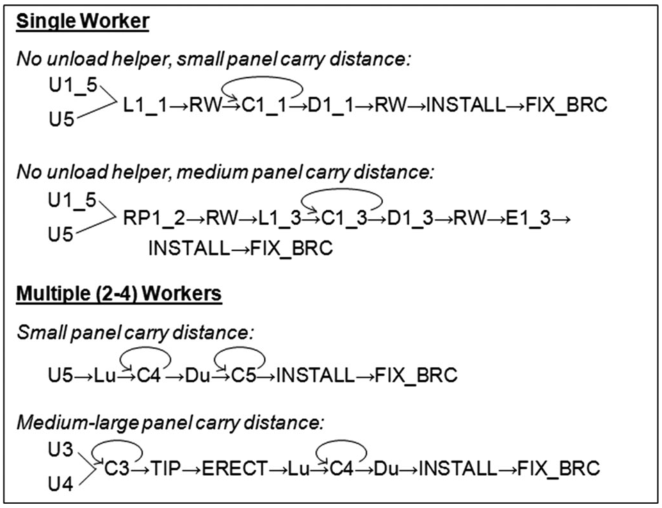


Fig. 6. Example activity class sequences for panelized residential construction.

to know the relationship between workers and the item during activity execution, as activity classes having similar relationships can be modeled (and thus coded) similarly. Based upon these ideas, seven different types of activity classes are recognized as follows:

1) *Type 1: Simple motion, attached moving workers*. The item undergoes simple motion (translation and/or rotation via a single continuous movement), definable via a single task. Workers move with the item, but do not change location/orientation with respect to the item—they act as if "attached" to it. A move rate is associated with the activity class: activity duration depends upon the move rate and the absolute magnitude of the move performed. Example: one or more workers carrying an item, in front of them, as they move it from point A to B.
2) *Type 2: Simple motion, unattached moving workers*. The item again undergoes simple motion, and workers move with the item. Here, however, workers simultaneously change location/orientation with respect to the item. A move rate or duration is associated with the activity class: in the former case, activity duration is calculated as before. Example: two workers pushing an item into place between two other items: as they move the item, they must change position with respect to the item in order to be out of the way.
3) *Type 3: Simple motion, stationary workers*. The item once more undergoes simple motion, but now workers remain stationary (no change in location or orientation). These activity classes typically cover small motions used to reposition/reorient an item at a particular location. Such motions are typically too small to get valid time estimates via activity rates and move distances: durations are thus necessary. Example: workers, holding an item off the ground, lower that item to the ground**.**
4) *Type 4: Complex motion via a sequence of tasks*. The item and/or workers undergo complex motion (multiple translation and/or rotation movements, each of which may

involve the item only, workers only, or both item and workers). The motion is defined via a sequence of tasks. For such activities, the following apply:

  a) The activity is modeled in low fidelity (i.e., approximated via some small set of tasks such that it is recognizable when the simulated activity is animated).
  b) Surrogate time/rate data is used for task durations. Any values can be used that are deemed to be in correct proportion to one another (in terms of the low-fidelity activity animation). If, for example, the second task is deemed to take roughly twice as long as the first, the first task can have any time *t* and the second is then 2*t*.
  c) Activity durations are required. Once this is established, individual task durations are scaled accordingly.

5) *Type 5: Complex motion via other activity classes*. The item again undergoes complex motion, but this is now defined via combinations of other activity classes. Each combination can consist of either of the following:
  a) One or more previously-identified activity classes. Activity duration is calculated directly by summing up the lower-level activity durations.
  b) One or more complex motion building block activity classes (see below). Activity duration must be established directly.
6) *Type 6: Complex motion building blocks*. As noted above, these are activity classes that serve as building blocks for Type 5 activity classes. They are modeled in a similar manner to Type 4 activity classes (i.e., low-fidelity modeling via a sequence of tasks, surrogate time/rate data used for task durations). Activity durations are established by determining parent activity duration and then scaling the durations of tasks comprising the building block activities accordingly.
7) *Type 7: Worker-only motion*. The item remains stationary, while one or more workers undergo translation and/or rotation. These are modeled in similar manner to Type 4 activity classes (i.e., task-based), the only difference being no items are involved.

Panelized residential construction example: Based upon the above, the 24 activity classes shown in Table I were modeled as follows:

1) *Type 1: Simple motion, attached moving workers:* all carry activity classes (C1_*x*, C*x*). Each of these consists of one or more workers translating or rotating the panel (*xy* plane) in a single motion, moving with the panel.
2) *Type 2: Simple motion, unattached moving workers:* E1_3 (single-worker panel erect). The worker rotates the sideways panel, resting on the floor, about one corner until upright: his location and orientation change with respect to the panel.
3) *Type 3: Simple motion, stationary workers:* all lift and drop activity classes (L1_*x*, L*x*, D1_*x*, Du). Worker(s) are stationary while the panel is raised (lowered).
4) *Type 4: Complex motion via a sequence of tasks:* RP1_2, TIP, ERECT, FIX_BRC, INSTALL. In each of these, the panel undergoes complex motion: a sequence of tasks is executed where in each case the panel only, worker(s) only, or both panel and worker(s) move.
5) *Type 5: Complex motion via other activity classes:* U1_5, U3, U4, and U5. In each of these unload activity classes, the panel undergoes complex motion, which can be represented via a combination of other activity classes. For example, U3 can be broken down into flat-panel unload when additional panel layers remain (U3_stk) or when the panel is taken directly off the floor (Lf).
6) *Type 6: Complex motion building blocks:* UL1, U3_stk, U45_rot, U4_pull, U5_Htip, U5_Vtip. These are building blocks for unload activity classes. For example, a panel can be rotated on the stack before removing in both U4 and U5 unloads. Thus, a separate activity class, U45_rot, is developed and used in both U4 and U5.
7) *Type 7: Worker-only motion:* RW. The worker rotates in place (*xy* plane) while the panel remains stationary.

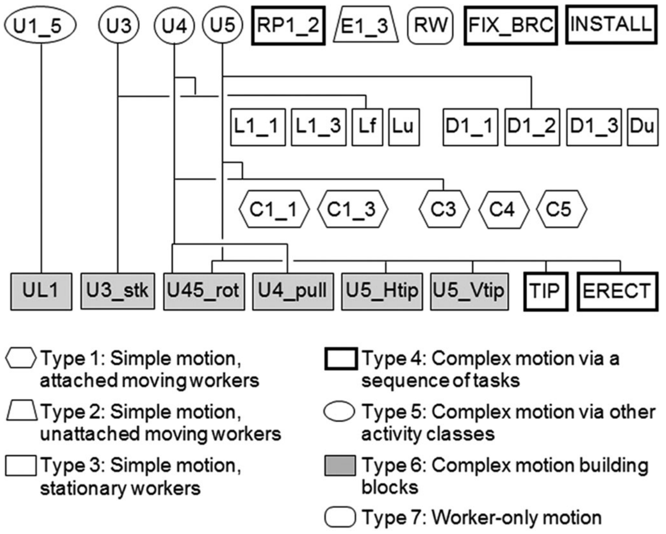


Fig. 7. Example activity classes used for modeling panelized residential construction.

The relationships between the resulting 30 activity classes (24 from Table I plus six complex motion building block activity classes) are shown in Fig. 7.

D. Identify Activity Types and Establish Time/Rate Distributions

As previously defined, an activity class represents a particular "way" workers perform some subprocess. As each activity class can cover a wide variety of scenarios (e.g., items of different sizes), however, it is necessary to further divide activity classes in order to obtain actual activities with which time/rate data can be associated. This leads to the idea of activity types for each activity class. Each activity type is a specific implementation of an activity class via a specific set of values for parameters associated with that class.

To establish activity types, it is necessary to observe a large variety of processing scenarios in action, focusing on the details. For each activity class, the first step is to identify the relevant parameters: these can roughly be grouped under quantity of workers, relative motion direction, item attributes, worker attributes, and scenario attributes. Possible values for each attribute are then established, and the combinations of possible attribute values result in the activity types. If a parameter is continuous or has an excessively large quantity of possible values, it may be necessary to establish a manageable set of discrete ranges to use. For each range, the activity type then represents an average (or worst-case) scenario.

Following the above, a time or rate sampling distribution must be established for each activity type. The data needed for this can be obtained via lab-based measurements or observation and data recording of the process (*in situ* or video). The distributions are then used to determine actual activity duration or rate during simulation execution.

Panelized residential construction example: The following parameters and values were identified via rigorous analysis of the panelized residential construction process (as described in Section IV-B):

1) Quantity of workers: 1–4.
2) Relative motion direction:
    a) *UNLOAD:* unload panel from FRONT, BACK, LEFT, or RIGHT of stack.
    b) *MOVE:* carry panel FWD (forward), BWKD (backward), LEFT, RIGHT, or TURN (rotate in place with panel).
3) Item attributes: panel size (dimensions) and weight, whether panel sheathed or not (results in additional weight and panel thickness).
4) Worker attributes: none (all workers considered identical).
5) Scenario attributes:
    a) *UNLOAD:* as panels are taken from a stack, stack height is reduced and thus worker hand positions, postures, etc., are constantly changing. Reasonable similarity was found, however, for panels within the bottom, middle, and top portions of each stack. Different unload activity types were thus specified for small (S), medium (M), and large (L) stacks.
    b) *INSTALL, FIX/BRACE:* eight scenarios were identified, each describing the already-finished panels to which panel P (being worked) will join. For example, P may join with a single finished panel on P's left side via a butt connection (INSTALL, Fig. 5), or a corner joint. Or P may need to be squeezed between two already-finished panels, etc.

All of the above parameters, except for panel size and weight, were used to establish activity types (panel size and weight can be directly correlated to the quantity of workers used). Based upon these parameters and values, 573 activity types were identified for the direct panel install processing strategy. Considering only the 24 activity classes shown in Table I, 437 activity types are obtained: the manner in which these are derived is shown in Table II. Examples of particular activity types and distribution data needed are as follows:

1) U5_BACKFRONT_2_L_SH: U5 unload panel from back or front of stack, 2 workers, low stack height, sheathed panel. Time distribution (sec.) needed.
2) C3_4_FWD: C3 carry, 4 workers, forward panel translation. Translation rate (m/sec.) distribution needed.

TABLE II
EXAMPLE ACTIVITY TYPES FOR PANELIZED RESIDENTIAL CONSTRUCTION

Activity Classes	Parameters[a]	# of Activity Types (each class)	Sampling Dist. Variable
U1_5	S/U panel	2	Time
U3	(B, L/R stack unload) × (2–4 W) × (L, M, H stack height) × (S/U panel)	36	Time
U4	(L/R stack unload) × (2–4 W) × (L, M, H stack height) × (S/U panel)	18	Time
U5	(B/F, L/R stack unload) × (1–4 W) × (L, M, H stack height) × (S/U panel)	48	Time
C1_1, C1_3	(move FW, L/R or TURN) × (S/U panel)	6	Trans. or rot. speed
L1_1, L1_3, RP1_2, D1_1, D1_2, D1_3, E1_3	S/U panel	2	Time
RW	LEFT (90° ccw), RIGHT (90° cw)	1	Worker rot. time
C3, C4, C5	(move FW, BW, L/R, or TURN) × (2–4 W) × (S/U panel)	24	Trans. or rot. speed
Lf, Lu, Du, TIP, ERECT	(2–4 W) × (S/U panel)	6	Time
INSTALL	((single worker) × (3 scenarios) + (2–4 W) × (8 scenarios)) × (S/U panel)	54	Time
FIX_BRC	((single worker) × (3 scenarios) + (2 worker locations) × (8 scenarios) +(3 worker locations) × (8 scenarios) +(4 worker locations) × (8 scenarios)) × (S/U panel)	150	Time

[a] S/U = sheathed/unsheathed, W = workers, L = low, M = med, H = high, B = BACK, F = FRONT, B/F = BACK/FRONT, L/R = LEFT/RIGHT, FW = FORWARD, BW = BACKWARD.

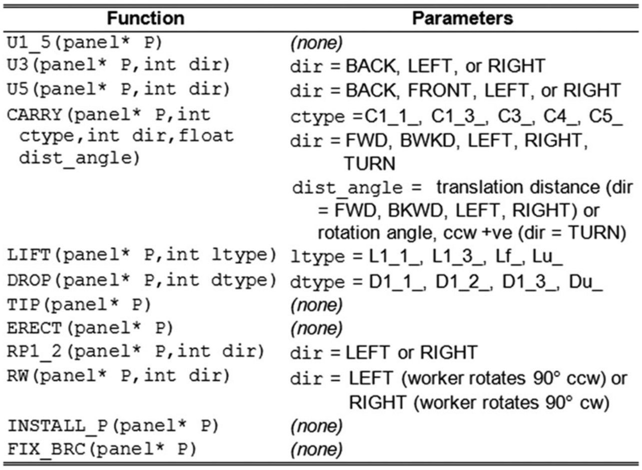
E. Improve Process Validity

At this point, physical processes are modeled via sequences of activity types. In other words, the process is obtained by stringing the activities together, one after another. Regardless of how accurate the individual activity type models are, however, this approach suffers from the fact that humans are not robots: they cannot perform one task or activity after another without any breaks or other delays. Additionally, as humans get fatigued, task performance suffers and the activities themselves are performed at reduced rates.

While consideration of fatigue is beyond the scope of this work, simple methods can be used to account for momentary pauses and breaks. This can be done at three levels:

1) Short deterministic or stochastic reset times between specific tasks, to account for brief pauses and/or minor changes in hand positions, posture, etc.
2) Medium stochastic activity reset time between activities, to account for longer pauses (e.g., worker stretches or pauses momentarily before continuing) and/or major changes in hand positions, posture, etc.
3) Longer stochastic changeover time at the start of the first major subprocess and between subprocesses.

TABLE III
EXAMPLE ACTIVITY CLASS FUNCTIONS FOR PANELIZED RESIDENTIAL CONSTRUCTION



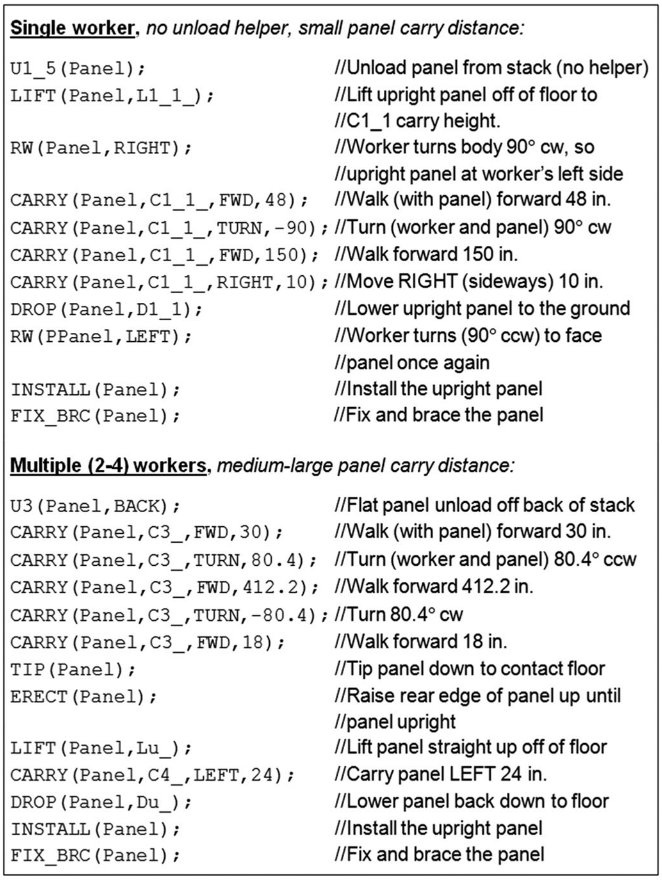
Function	Parameters
`U1_5(panel* P)`	*(none)*
`U3(panel* P,int dir)`	`dir` = BACK, LEFT, or RIGHT
`U5(panel* P,int dir)`	`dir` = BACK, FRONT, LEFT, or RIGHT
`CARRY(panel* P,int ctype,int dir,float dist_angle)`	`ctype` =C1_1_, C1_3_, C3_, C4_, C5_ `dir` = FWD, BWKD, LEFT, RIGHT, TURN `dist_angle` = translation distance (dir = FWD, BKWD, LEFT, RIGHT) or rotation angle, ccw +ve (dir = TURN)
`LIFT(panel* P,int ltype)`	`ltype` = L1_1_, L1_3_, Lf_, Lu_
`DROP(panel* P,int dtype)`	`dtype` = D1_1_, D1_2_, D1_3_, Du_
`TIP(panel* P)`	*(none)*
`ERECT(panel* P)`	*(none)*
`RP1_2(panel* P,int dir)`	`dir` = LEFT or RIGHT
`RW(panel* P,int dir)`	`dir` = LEFT (worker rotates 90° ccw) or RIGHT (worker rotates 90° cw)
`INSTALL_P(panel* P)`	*(none)*
`FIX_BRC(panel* P)`	*(none)*

Panelized residential construction example: A task reset time of 2 s was employed between tasks, where workers change grip or how a panel is held (e.g., U3_stk: reset time between workers pulling the panel clear of stack and then raising/lowering the panel). Activity reset time was randomly generated per a uniform distribution between 0 and 10 s, except for in-between panel translate/rotate activities (C1_x, Cx) where the upper limit was 5 s. Subprocess start/changeover time was similarly generated but was between 2 and 5 s. These parameters were established from analysis of video recordings of the panelized residential construction process.

F. Code-Up Activity Classes and Process Modeling "Language"

To utilize the activity classes and types developed per the above in a simulation, they must be coded so they can be used in a simulation program (either commercial software calling these as routines, or within a stand-alone software program). Each activity class becomes a function: the collection of functions becomes the language used for both modeling and simulating the multiworker physical processes. The most flexible approach is a stand-alone object-oriented discrete-event simulation program, written using a high-level language such as C++. With this approach, the items and workers are objects in the simulation: they "know" and "track" their own location/orientation and which items they are associated with. Additionally, each worker can keep a record of what moves he has made, with which other workers and what items, and at what times. These aspects simplify function definition and development as well as provide a framework for obtaining the data which will be needed later for ergonomic assessment.

Panelized residential construction example: The process modeling language (functions), developed using object-oriented modeling and C++, is shown in Table III. All functions pass the panel object of concern: each panel tracks its location/orientation, as well as which workers are associated with it. These worker objects, in turn, track their own location/orientation. Thus, the various parameter values needed by each function (quantity of workers, whether panel sheathed or not, etc.) for a particular activity type can be determined from these objects directly: such data do not need to be passed in the function call. Higher level functions (CARRY, LIFT, and DROP) have been incorporated to facilitate use of the related activity classes. Examples of single- and multiple-worker panel process plans, following the first and last activity class sequences of Fig. 6 and specified via the functions in Table III, are provided in Fig. 8.



Single worker, *no unload helper, small panel carry distance:*

```
U1_5(Panel);                    //Unload panel from stack (no helper)
LIFT(Panel,L1_1_);              //Lift upright panel off of floor to
                                //C1_1 carry height.
RW(Panel,RIGHT);                //Worker turns body 90° cw, so
                                //upright panel at worker's left side
CARRY(Panel,C1_1_,FWD,48);      //Walk (with panel) forward 48 in.
CARRY(Panel,C1_1_,TURN,-90);    //Turn (worker and panel) 90° cw
CARRY(Panel,C1_1_,FWD,150);     //Walk forward 150 in.
CARRY(Panel,C1_1_,RIGHT,10);    //Move RIGHT (sideways) 10 in.
DROP(Panel,D1_1);               //Lower upright panel to the ground
RW(PPanel,LEFT);                //Worker turns (90° ccw) to face
                                //panel once again
INSTALL(Panel);                 //Install the upright panel
FIX_BRC(Panel);                 //Fix and brace the panel
```

Multiple (2-4) workers, *medium-large panel carry distance:*

```
U3(Panel,BACK);                 //Flat panel unload off back of stack
CARRY(Panel,C3_,FWD,30);        //Walk (with panel) forward 30 in.
CARRY(Panel,C3_,TURN,80.4);     //Turn (worker and panel) 80.4° ccw
CARRY(Panel,C3_,FWD,412.2);     //Walk forward 412.2 in.
CARRY(Panel,C3_,TURN,-80.4);    //Turn 80.4° cw
CARRY(Panel,C3_,FWD,18);        //Walk forward 18 in.
TIP(Panel);                     //Tip panel down to contact floor
ERECT(Panel);                   //Raise rear edge of panel up until
                                //panel upright
LIFT(Panel,Lu_);                //Lift panel straight up off of floor
CARRY(Panel,C4_,LEFT,24);       //Carry panel LEFT 24 in.
DROP(Panel,Du_);                //Lower panel back down to floor
INSTALL(Panel);                 //Install the upright panel
FIX_BRC(Panel);                 //Fix and brace the panel
```

Fig. 8. Examples of process plans for panelized residential construction specified via high-level modeling language.

G. Incorporate Code in Simulator

As previously discussed, the simulation program in the proposed approach is actually a simulator, and as such can be used for different problems within the specified domain. The activity class functions developed per the previous section are incorporated into the simulator, along with the process planning logic established earlier (see Section IV-B), as shown in Fig. 2. For a given problem, the process planning logic generates a process plan which specifies how the process is to be performed, articulating this plan via the activity class functions. This plan is then used to drive the simulation. Animation capability can also be incorporated directly into the functions, if desired.

Panelized residential construction example: An object-oriented panelized residential construction simulator was coded and implemented using C++. Activity class functions were maintained in a separate file, declared as external functions in the main simulation program, and linked during compilation.

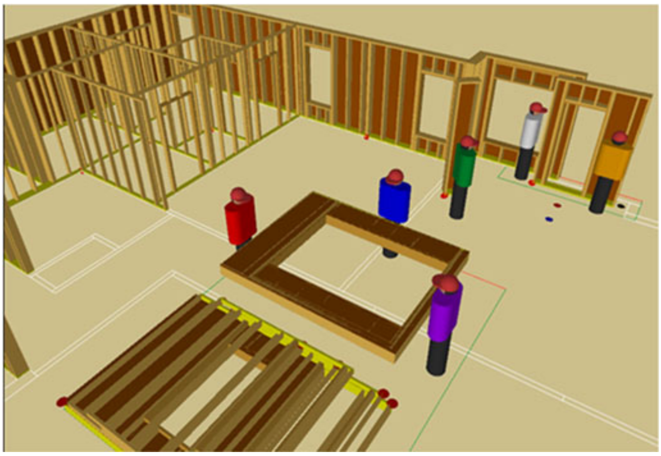


Fig. 9. Example of animation of simulated panelized residential construction, showing *UNLOAD*, *MOVE*, and *INSTALL* subprocesses.

Panel processing logic was similarly maintained and linked as a separate file. For a given residential panelized construction problem (house plan, crew size, panels stacking definitions, stack drop-off locations and timing, etc.), panel processing logic generates a process plan for each panel. Each such plan specifies what workers are used, how the panel is unloaded and moved, etc., and is articulated via the functions shown in Table III (the example plans of Fig. 8 were generated automatically in this manner). These plans drive the panelized residential construction simulation. The simulator also provides process animation using PROOF 3D (Wolverine Software Corporation): an example animation snapshot is shown in Fig. 9. Further details regarding the simulator and animation capabilities are beyond the scope of this paper.

V. ERGONOMIC ASSESSMENT METHODOLOGY

A. *Identify and Model Ergonomic Tasks*

As described in Section III, detailed ergonomic assessment is performed for those loads which result in high-risk exposure to workers performing complex physical processes: the associated tasks are referred to as ergonomic tasks. To identify and characterize ergonomic tasks, the activities established as described in Section IV (or via a separate modeling exercise) must be studied in detail. Hierarchical task analysis, work sampling, and/or worker interviews can be used to obtain additional information regarding activity frequency, characteristics, item handling techniques, and physical demands. Ergonomic task types are established first: each of these becomes one or more ergonomic tasks based upon whether or not workers perform the tasks in fundamentally different ways for different parameters (e.g., relative item location).

Panelized residential construction example: A taxonomy of panelized wall construction activities was developed based upon video recordings and worker interviews for the construction of ten different homes [2]. Four ergonomic task types were identified (lifting, carrying, erecting, and moving) and ten ergonomic tasks were established, based upon different panel starting heights and handling techniques. Eight of these ergonomic tasks are shown in Table IV.

TABLE IV
ERGONOMIC TASKS AND CORRESPONDING ACTIVITY CLASSES, PANELIZED RESIDENTIAL CONSTRUCTION

Ergonomic Task		Activity Classes
Identifier	Description	
L1G	Lift flat panel straight up from ground to knuckle height (worker standing)	Lf
L1K	Lift flat panel off of stack to C3 position	Task within U3_stk, U4_pull
C1	Carry flat panel	C3, dir = FWD, BKWD, LEFT, RIGHT
M1	Move (slide) upright panel along floor, in direction parallel to panel's length	C5, dir = LEFT, RIGHT
EIGTop	Erect flat panel from ground, top (middle) worker(s), three or four workers	ERECT
EIGSide	Erect flat panel from ground, side workers, three or four workers	ERECT
ElKTop	Erect flat panel from knuckle height, top (middle) worker(s), three or four workers	TIP + ERECT
ElKSide	Erect flat panel from knuckle height, side workers	TIP + ERECT

B. *Develop Ergonomic Equations*

For each ergonomic task, appropriate ergonomic assessment methods must be identified and/or developed. Because of the broad range of parameters (e.g., item length, mass, relative location, and quantity of workers) that can be associated with a task, it is often infeasible to assess ergonomic risks for the entire range of each parameter that can occur during physical processing. To cope with this, models are developed for each task to predict ergonomic risk: the models consider only task-related parameters as predictors and not detailed body kinematics, as this level of detail is not provided by the simulation. Once the models have been established, the relevant kinematic/kinetic data needed to parameterize each model can be obtained (e.g., from laboratory experiments). This "task-based" approach assumes that risks are comparable for each worker doing a given task. To simplify ergonomic output analysis, the continuous output of such models can be discretized and normalized to a small set of possible values, each indicating a different relative level of ergonomic risk.

Panelized residential construction example: We used several ergonomic assessment methods (e.g., [27], [28]) to quantify relative ergonomic risks for each task with respect to panel mass and length [3] and the availability of an additional worker [29]. For lifting and erecting tasks, for example, a regression model was developed of the form

$$Y = b_0 + b_1 H_0 + b_2 M + b_3 L + b_4 NW + \text{Higher order and interaction terms} \quad (1)$$

where Y is the outcome measure from the respective ergonomic assessment method, $b_0 - b_4$ are regression coefficients, and H_0, M, L, and NW are the panel height (m), mass (kg), length (m), and the number of workers involved, respectively. To establish and validate the regression coefficients, two separate laboratory studies ($n = 24$ and 10, respectively) were performed: these involved tasks with different combinations of three panel lengths, two panel masses, and additional worker availability (see [3] for experimental details). Body kinematics required for some ergonomic assessment methods [e.g., the rapid entire body assessment (REBA)] were obtained using a passive optical motion capture system (Vicon Motion Systems, U.K.). Final regression models are currently being identified and validated. By example, an equation for the REBA score for L1K has been obtained as

$$\begin{aligned} Y &= 3.96 + 0.77H_0^{-1} + H_0^{-2} \\ &\quad \cdot (-0.025 + 0.00027L - 0.0000076M) \\ &\quad + L\,(0.017 + 0.026H_0) - 0.03H_0NW. \end{aligned} \tag{2}$$

As previously outlined, the ergonomic equations are incorporated into an "ergonomics assessment engine" (see Fig. 2). Output from the ergonomic equations is further processed to obtain a three-level output for a given task, using the common traffic light analogy (i.e., red, yellow, and green) based on action limits defined in the respective ergonomic assessment methods. This approach (e.g., [30]) allows the rather extensive detailed outputs across workers and tasks to be compiled and more easily interpreted. For example, probability or cumulative distributions of ergonomic assessments can be obtained across workers and/or crews for a given structure.

C. Correlate Ergonomic Tasks With Activity Classes

Each ergonomic task identified above will correspond to either 1) a particular activity class, or 2) one or more tasks within a particular activity class. The manner in which each ergonomic task is represented is first determined. Following this, the "activity class functions" code in the simulator (see Fig. 2) is modified so that for each ergonomic task the appropriate worker and item location/orientation data is recorded when the corresponding activity is executed.

Panelized residential construction example: Ergonomic tasks correlate to activity classes/tasks as shown in Table IV.

D. Generate Motion Script During Simulation

As outlined in Section IV-G, process planning logic within the simulator generates a process plan specifying exactly how a given process is to be performed, articulating this plan via activity class functions. During simulation, the functions are executed, in order, when the activities are to occur: this is accomplished via traditional discrete-event simulation logic (see Fig. 2). Each time a function is executed, location/orientation data pertaining to that item and workers is written to a file ("motion script") for postprocessing.

Panelized residential construction example: Table V shows part of the motion script for the multiworker panel processing example of Fig. 8. In this particular realization, panel #27 is being processed by workers 3, 5, and 6. Note that the second forward flat panel move of 412.2 in (10.47 m) appears in four separate ergonomic tasks (120.0, 120.0, 86.1, and 86.1 in). This results from a simulation subroutine that breaks up long move activities into smaller ones, to facilitate the interaction of multiple workers and panels.

TABLE V
EXAMPLE MOTION SCRIPT GENERATED VIA SIMULATION OF PANELIZED RESIDENTIAL CONSTRUCTION

Time	Panel							Workers	
(sec)	#	Ergo task	ZLoc	dX	dY	dZ	distance	qty	IDs
349.0	p27	L1K	69.0	0.0	0.0	−37.0		3	5 3 6
367.4	p27	C1	32.0	0.0	30.0	0.0	30.0	3	5 3 6
390.3	p27	C1	32.0	−118.3	19.9	0.0	120.0	3	5 3 6
393.2	p27	C1	32.0	−118.3	19.9	0.0	120.0	3	5 3 6
396.1	p27	C1	32.0	−84.9	14.3	0.0	86.1	3	5 3 6
398.2	p27	C1	32.0	−84.9	14.3	0.0	86.1	3	5 3 6
426.5	p27	C1	32.0	0.0	18.0	0.0		3	5 3 6
432.9	p27	E1KSide	32.0	0.0	0.0	0.0		2	5 3
432.9	p27	E1KTop	32.0	0.0	0.0	0.0		1	6

E. Process Motion Script to Generate Ergonomic Assessments

Once the motion script for a given processing scenario has been generated, ergonomic measures are calculated via the ergonomics assessment engine as previously described.

Panelized residential construction example: Some of the ergonomic assessment methods used are applicable to all ergonomic tasks, and REBA is one example. Thus, REBA scores and corresponding three-level outputs are presented for the multiworker processing example of Fig. 8 and motion script of Table V as follows:

1) L1K: 4.4 (Yellow)
2) C1: 5.0 (Yellow)
3) E1KSide: 5.2 (Yellow)
4) E1KTop: 4.5 (Yellow).

VI. DISCUSSION

The proposed approach and methodology for simulation modeling and ergonomic assessment of complex multiworker physical processes was successfully applied to panelized residential construction, resulting in software which can be used for designing any panelized house keeping ergonomic considerations of the construction workers in mind. This exercise showed that while application of the proposed approach and methodology is relatively straightforward, it also requires a great amount of work. As witnessed through the example, extensive study and effort are needed on four fronts:

1) Modeling the process details: identification of subprocesses, processing strategies, activity classes, activity class sequences, and activity types. The process must be observed in action, whether *in situ* or via video recordings, for a very large number of scenarios.
2) Establishing sampling distributions for activity types. As previously described, there were 573 distributions to generate for panelized residential construction where panels are installed directly. Laboratory experiments or video analysis were needed to generate the necessary data for each of these. In the latter case, the time required for each can be significant, as the observations must be located in the video tracks.
3) Coding up the activity classes and developing the process modeling language. This was a major coding effort, resulting in over 8500 lines of C++ code. Extensive

effort was also needed to code-up a test simulation and animation facility (for debugging).

4) Performing the laboratory experiments to establish the ergonomic assessment models.

Overall, application of the proposed approach and methodology to panelized residential construction took about two person-years. Additional time was needed to develop the simulator itself and animation capability (not described in this paper). Of particular note is the need for 3-D animation to support simulation modeling. Though not inherently necessary for executing the proposed approach and methodology, the panelized residential construction example indicated that it would be extremely difficult to code-up the activity functions without having animation capability for code verification and debugging.

While the time and effort needed for the proposed approach may seem excessive, it must be remembered that the end product is a simulator which can be used for any problem within that domain, not just a simulation model for a specific process. The approach can thus be cost-effective for problem domains where the following apply:

1) Process complexity is such that simulation is the only viable modeling alternative.
2) The set of possible processing scenarios is large and situation dependent and, thus, cannot be established with certainty in advance.
3) Ergonomic risk to the workers involved is substantial.
4) The process currently exists in physical form, such that isolated tasks can be properly studied and analyzed, and
5) The process has a long lifespan (due to the time and effort involved).

All of these characteristics were present for panelized residential construction. Regarding modeling validity and ergonomic assessment, some limitations are inherent in our approach. Though the task-based approach to ergonomic risk assessment being used is common and generally accepted (e.g., [31], [32]), it is not without limitations. For example, individual factors (e.g., age, height) are not considered, though exposures for a range of workers are available from the noted lab studies. Time-dependent exposure levels (e.g., task sequence, fatigue) are also not incorporated. These limitations largely result from a lack of good contemporary analysis tools. As future research provides these tools, they can easily be incorporated. Our approach to ergonomic risk assessment also focuses on the fundamental tasks associated with the given multiworker physical processing scenario. Other tasks having lower levels of exposure are not examined, but future work could more formally assess and include these additional tasks.

While the current approach provides detailed assessments of ergonomic risks, challenges remain in specific interpretations of such model-based outputs. It is generally unclear, based on current evidence, how to best integrate ergonomic exposures across tasks, over time, and/or at the crew level. Insufficient evidence exists, for example, to establish how to compile diverse assessments obtained from multiple ergonomic assessment tools and/or for risks at different body regions. Similarly, while cumulative (or accumulated) loading appears to be an important exposure/risk metric (e.g., [33], [34]), a specific quantitative approach to draw action limits from cumulative loading remains to be developed (e.g., [35], [36]). Fatigue, whether at the whole-body or more localized levels, is another aspect that is not currently incorporated: at the crew level, there is again limited evidence to guide interpretation. Over time, however, as effective approaches are identified, each of these current limitations can be addressed by incorporating additional algorithms or through additional compilation/processing of the system outputs. Furthermore, future improvements in DHM may obviate, or at least reduce, the need for detailed time-consuming lab studies as was done here.

Finally, the potential problem of coordination between the simulation and ergonomic sides of the proposed approach and methodology must be kept in mind. Because this work requires expertise in each of these areas, there will undoubtedly be both simulation and ergonomics experts involved: effort will be required to ensure that these parties can work together in as seamless and productive a manner as possible. In the panelized residential construction effort, for example, the process analysis and modeling exercise was in fact performed twice: once from the ergonomics side and again from the simulation modeling side. Additional effort was then required to "combine" the two models into one (see Table IV). It is believed that some duplication of effort due to the above-stated reasons is unavoidable. Steps to minimize the impact and adverse effect of such efforts, however, can and should be planned into the implementation process.

In conclusion, the proposed approach and methodology provide a viable (though time-consuming) mechanism for simulation modeling and ergonomic assessment of complex multiworker physical processes. It allows us to establish and study ergonomic implications for processes where this would otherwise be unattainable: the end result is a simulator which can be used for any problem within a specified domain. The approach and methodology were successfully demonstrated for the panelized residential construction process. Other domains to which the approach and methodology could be successfully applied include manufacturing plants concerned with make-to-order or assemble-to-order production of large items (i.e., multiple workers needed for item handling), warehousing facilities and distribution centers where large items are frequently encountered, shipyard operations (multiyear lead times for large ships, wide variety of heavy components and assemblies), and military setup operations such as bridges and field hospitals (activities similar to panelized residential construction).

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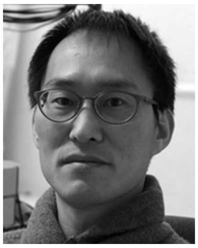

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