AGENT-BASED MODELING OF WORKER SAFETY BEHAVIOR AT THE CONSTRUCTION WORKFACE

Kenneth D. Walsh[1] **and Anil Sawhney**[2]

ABSTRACT

A great deal of research has been directed toward developing intervention strategies for improving safety performance in construction. While the construction research community has become more enlightened about the degree to which accidents can be blamed on workers, nonetheless it must be acknowledged that a certain amount of risk-taking by workers is often involved. This behavior seems contrary to self-interest, because while the consequences to the project or the employer have been measured economically, the consequences of an incident to the worker are more direct, immediate, and severe. In spite of this perceived action against interest, incidents still occur. To consider possible connections between employer attitudes regarding production and reward systems put in place by the employer and resulting worker behavior, an agent-based simulation experiment was conducted. In this experiment, different employer attitudes and reward systems could be modeled and experienced by a population of workers with variable degrees of native production ability and risk-tolerance, while these workers conduct operations on a simulated project site of spatially-variable danger. By using an agent-based approach, local and random interactions and events can occur and lead to emerging measures for the entire system, in much the same way that local interactions lead to a gross metric such as incident rate. The experiment demonstrates a link between employer attitudes and reward structures and the distribution of risk-tolerance in the worker population. The impact of interactions between workers and the level of danger at the site is considered.

KEY WORDS

Construction safety, agent-based modeling, simulation, risk tolerance.

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[1] AGC-Paul S. Roel Chair in Construction Engineering and Management, Department of Civil and Environmental Engineering, San Diego State University, San Diego, CA 92182-1324, TEL:619/594-0911, FAX: 619/594-8078, kwalsh@mail.sdsu.edu

[2] Associate Professor, Del E. Webb School of Construction, Arizona State University, Tempe, AZ, 85287-0204, TEL: 480/965-7417, FAX: 480/965-1769, anil.sawhney@asu.edu

INTRODUCTION

Significant research has been conducted in construction to develop an economic case for safety in the industry. There are variations, of course, but in general the argument proceeds along the lines that the cost of an incident – in increased insurance cost, lost productivity, and disruption – provides an economic motivation to try and prevent incidents (Hinze 2000). As a result of such findings, construction managers have undertaken significant efforts to develop safety management strategies in order to reduce safety incidents in the construction sector, and construction-related incident rates have in fact decreased in the United States over the past three decades (Figure 1).

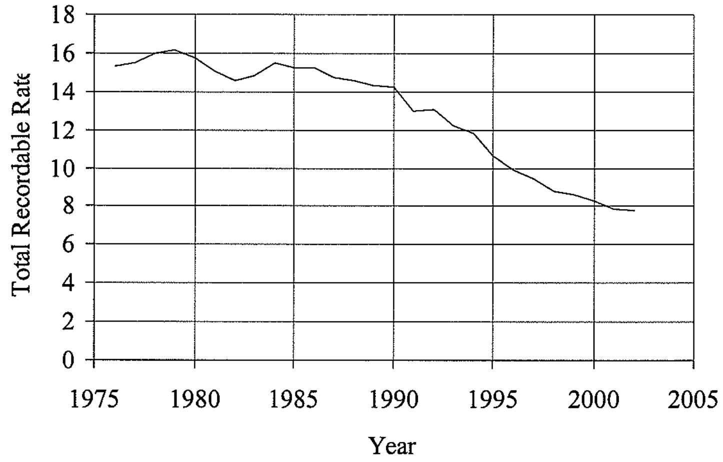

Figure 1: U.S. Recordable Incident Rate Time History for Construction Sector. Source: US BLS

While the trend depicted in Figure 1 is indeed favorable, it still leaves the construction industry as one of the most dangerous industries for employment. The loss or injury of trained and experienced workers, and the attendant disruption to progress of work, undeniably represent waste in the performance of construction. In order to eliminate this waste, one might reasonably seek an understanding of the underlying causes of construction incidents (see for example Arboleda and Abraham, 2004).

There is a significant body of literature on this very question, of course. Much of this literature offers very detailed and technical analysis of incidents or injuries of particular types. Such research is not of primary interest here. Rather, the authors were interested in understanding the oft-referenced concept of a "safety culture" (Kallas-Tarpila et al. 2003). This term, which is not precisely defined, connotes the combination of management attitudes and activities, worker peer interaction, and the physical environment of the site. Anyone with direct experience with high-performing and low-performing safety cultures can attest to the importance of this concept, but it is not clear how this idea is translated as worker behavior and expressed as incidents.

Al-Tabtabai (2002) studied the general concept of safety culture, and indicated that the most important factors in construction site accidents were management policies (such as safety meetings, training, and supervisory attitudes and messages) and risk acceptance by workers (such as working without protective equipment or ignoring safety rules). Arboleda and Abraham (2004) also maintain a distinction between management attitudes and worker behavior. The authors found this construct, in which management activities and worker activities are viewed as separate but related phenomena, to be very useful as a means of analyzing and categorizing safety culture. On the worker side of this construct, Johnson, et al. (1998) found worker risk-taking behavior to be a significant contributor to fall injuries. Fredericks et al. (2002), Welch et al. (2001), and Kines (2002) identified injuries occurring to workers who lacked appropriate personal protective equipment (PPE). On the management side of the construct, Lee and Halpin (2003) showed that supervision and training were related to safety performance. Gerber and Yacoubian (2001) showed the prevalence of the risk-taking behavior among those working under the influence of drugs, but found that aggressive management intervention in the form of random testing could dramatically improve safety performance. Harper and Koehn (1998) present a case study in which management interventions affect worker safety metrics.

If safety culture affects worker behavior, if management attitudes and behavior are a key part of the safety culture, and if the management structure and personality are likely to vary from project to project, then it should be found that safety outcomes vary with changes in project management approach or safety attitude. Indicating that this might be the case, Lingard and Holmes (2001) studied small trade contractors and concluded that the variability of work environments and safety cultures from site to site create a perception that individual risk tolerance is a controlling factor in safety performance. Along similar lines, Spangenberg et al. (2002) point out that short periods of contact with a safety intervention program can reduce the effectiveness of the program, and speculate that increased residence time with a given safety program may improve results, perhaps owing to the ability of workers affected to internalize the new program.

The foregoing studies suggest that there is inter-dependency between the attitudes and behaviors of the construction management and corresponding worker attitudes and behaviors about their own safety. The existence of such a relationship may or may not be self-evident, but the structure and function of this relationship is far from clear. Zoller (2003) found interaction between worker behavior and management initiatives to be more subtle and discursive than expected from a command-and-control management model. In this paper, we have attempted to understand how management attitudes affect worker safety behavior via an agent-based simulation experiment. The approach is abstracted from real-world system, but provides interesting insights for further testing.

AGENT-BASED SIMULATION EXPERIMENT

AGENT-BASED SIMULATION

Agent-based simulation (ABS) is a methodology in which a simulation experiment is constructed around a set of autonomous "agents" that interact with each other and their underlying environment to mimic the real-world scenario that they model (Sanchez and Lucas 2002). ABS closely resembles how physical, biological, and social systems work in their natural form (Walsh et al. 2003). Some consider this technique a new development; while others simply deem it as a natural extension of existing paradigms such as parallel and distributed discrete-event simulation, and object-oriented simulation (Davidsson 2000). ABS has been used in a variety of fields including social sciences, ecology, economics, political science and marketing and sales (Bonabeau 2002). Some applications in the construction sector have been attempted (e.g. Goldstein et al 2004), but few directly at the level of construction processes.

Agent-based models allow the modeler to engender an electronic interaction between virtual agents in a virtual environment. It is an ideal platform for problems in which individual actions, perhaps informed by individual properties, experience, or background, are significant to the outcome of a given event, and in which random interactions between participants or between participants and their environment are part of the phenomenon under study. Such models are often used to attempt to understand complex outcomes which might arise from simple, rule-based interactions at a local level. It is important to note that duplication of reality is usually not the intention. Rather, the modeler aims to understand complex phenomena by producing a simplified simulated environment, and then seeking to establish rules that lead to results in keeping with the complex reality. The resulting rules offer insights into the manner in which local decisions can affect the complex system.

The simulations described in this paper were conducted using the simple agent-based environment Starlogo (Colella et al. 2001, education.mit.edu/starlogo/). Once the agents and the environment are programmed, agents can move around in their environment, can interact with their environment, and can interact with other agents. The following activities must be completed in order to conduct an agent-based modeling experiment:

- **Define the environment:** This activity includes basic definitions such as the boundaries of the environment. It also includes other characteristics that might be important for a given model, such as temperature, concentration of food, elevation, ground cover, etc., as well as rules by which these characteristics might change, if appropriate. For the present case, the environment was defined to represent the construction site. It is not necessary to delve deeply into the details of the geometry and complexity of the site, nor the degree to which it is changing with time. Indeed, incorporation of such detail into the model can very easily obscure the fundamental behavior under study. Therefore, for this model the site was represented by a rectangular area (31 units wide and 50 units high) with varying degrees of danger from place to place around the site. The degree of danger was represented by a variable called *danger*, which was allowed to vary with a normal distribution between 0 (very safe locations where no injury is likely regardless of worker care) and 200 (very dangerous locations where workers will have to exhibit caution in order to avoid injury). The average and the standard deviation of *danger* can be controlled by the user.
- **Define the rules for agents to interact with the environment:** Agent interactions with the virtual environment are rule-based. In this activity, one must work out what rules are required to model the system of interest. For the present case, the interaction

was defined by the relationship between the danger at a given location and the degree of caution exercised by the worker agent. Worker agents move around in the construction site to accomplish tasks. Again, the details of these tasks are not modeled. The worker agents' activities on the construction site are modeled simply by the task of traveling back and forth across the site along a given line. Each time they make a round trip, they are deemed to have completed a task. A running sum of the number of round trips completed by each agent is kept in its *production* counter. In addition to this counter, worker agents have two inherent characteristics: *speed* and *caretaken*. The *speed* characteristic is an integer variable which ranges from 1 to 5, and describes the number of units of distance a worker will cover in a given time step. Hence, a worker with a *speed* of 5 will require about 6 time units to cross from one side of the site to the other. The *speed* characteristic stands in for the level of production of some task, and is assumed to be an inherent characteristic of the worker. The idea that different workers exhibit different native productivities is well-established, of course (e.g. Taylor 1917). The average and standard deviation of the *speed* value for the initial worker agent population is user-controlled.

The worker exhibits an inherent level of care described by *caretaken*, which is allowed to vary between 0 and 200, with the average and standard deviation of the initial population also user-controlled. The employee is assumed to have an innate level of care, represented by the variable *caretaken*, which represents the degree of risk a given employee is comfortable with. It is perhaps debatable whether this variable is in fact an inherent characteristic of the employee, or whether the employee's awareness of job conditions influences this variable. Zoller (2003) found worker acceptance of risk to be largely an innate characteristic in an automotive environment. Similarly, despite awareness that the speed of one's automobile is a factor in the probability and severity of accidents, a significant fraction of the population is comfortable exceeding posted speed limits. However, some people in the authors' acquaintance are comfortable at speeds much higher than the authors, and this characteristic seems not to be affected by time so much as the probability of being observed and ticketed by police. In any case, as will be described later, the model will also allow for learning to influence worker safety behavior and the *caretaken* variable.

While moving around in the site, the worker agents interact with the environment through the relationship between *caretaken* and *danger*. The interaction can be summarized as follows:

- When *caretaken* for an agent at a given location >= *danger* at that location, the worker is exhibiting a level of care at least appropriate to the conditions at the present location on the site, and so no incident will occur (at least in the simplest model).
- When *caretaken* < *danger*, the worker is exhibiting a level of care below that appropriate to the conditions at that location and one of two outcomes result:
    - Possibly, no incident at all may take place. In this case, the worker can be thought of as having "gotten away with it." For example, this might represent the case in which a worker enters a trench with vertical walls and

  no shoring, a dangerous condition by any standard, and yet no trench failure occurs.

- Alternatively, the worker is involved in an incident. Two outcomes are possible in this case:
  - Recordable, non-fatal incident – Each worker maintains a count of the number of incidents to which they have been subject (*SafeInc*). If the incident is non-fatal, this count is increased by one, and the worker goes about their business. There is no attempt to model lost time; rather, a given time step in the model represents an equal amount of productive time for all workers, not an equal quantity of elapsed time.
  - Fatal incident – In this case, the worker is killed in the incident. The agent representing the worker is deleted, and a new agent is created to replace them. The probability that an incident will occur when the worker is at risk (that is, when *caretaken* < *danger*) is user-controllable, as is the average and standard deviation of the level of danger on the site. The user can also modify all the probabilities associated with the occurrence and severity of an incident.
- **Define the rules for agents to interact with other agents:** In this activity, one must describe what happens in the case where agents are "close enough" to interact with each other. This step would be required in the general case, but in the present study the agents are left unaware of one another. Worker agents move back and forth across a given line, and for the most part they are unaffected by the progress of other surrounding agents. This situation is probably acceptable for some trades, and unacceptable for others, but in the present model the agents do not interact with each other, and do not change the *danger* at locations on the site.

VALUE MODEL

Management influences worker behavior only indirectly in the model, via a representation of the values of the project management. These values are explicitly stated via weights applied to productive and safe behavior. The value proposition is expressed in Equation 1:

$$\text{Score} = (\text{ProdWt})(\text{Production}) - (\text{SafeWt})(\text{SafeInc}) \quad (1)$$

where *ProdWt* and *SafeWt* represent the weight given to high levels of production and safe behavior, respectively. An agent's *Score* is used to provide a mechanism for a genetic algorithm to model the development and learning of the workforce. The process is patterned after the prisoner's dilemma models reported by Axelrod (1997).

With the environmental conditions and worker agent rules as described above, the simulation could proceed. The process can be summarized as outlined below:

1. Setup the model: Instantiate the construction site, with *danger* randomly assigned to each cell from a normal distribution based on a user-controlled average and standard deviation. A population of 50 worker agents was instantiated into the site. Each worker was assigned a random production level from a uniform distribution of *speed* from 1 to 5. To highlight the management decision, *caretaken* and *speed* were

inversely related to one another for this study, with faster workers assumed to exhibit less care. In this case, the variation was linear, between (*speed* = 5, *caretaken* = 100) and (*speed* = 1, *caretaken* = 200). This relationship is in keeping with conventional wisdom, but is not necessarily true for all construction activities, nor necessarily appropriate in scale. Hinze (1997) implies that such relationships may exist in some cases. However, Bernhold et al. (2001) demonstrate that increased safety performance need not affect productivity, despite conventional jobsite wisdom.

2. For each time step, the workers would:
   a. Determine how far to move during this time step. This determination was made based on the following:
      - The worker's speed value
      - The nearness of the edge of the site: If a move at full speed would send them past the edge, then their speed would be reduced to just reach the edge..

   b. Move the distance determined in the previous time step.
   c. Assess the safety situation at the new location. This determination is based on the relative value of *caretaken* of the worker and *danger* of the current location, as previously described.

Step 2 above was repeated for 1000 time steps. During those 1000 steps, workers would accumulate *production* and *SafeInc* values, and thus develop a spectrum of *Scores.* Any workers involved in fatal incidents were replaced with new workers. These new workers were assigned a value of *production* and *SafeInc* equal to the average of all other workers on the site, in order to avoid penalizing them for shorter service, and were assigned a random *speed.* The *caretaken* for the replacement agent was computed from the *speed* variable, as for new agents.

To simulate learning and development of the workforce, a genetic algorithm was employed. After 1000 time steps, the workers were ranked by the *Score* calculated from their accumulated results over the preceding 1000 time steps, which in turn is based on the weights assigned to production and safety by the user. The 6 workers with the lowest scores were removed from the model, leaving 44 worker agents behind. The 12 highest-ranking workers in this remaining set were then used to create 12 new workers. The new workers were assigned a *speed* and *caretaken* value by averaging the values of the 12 highest ranking workers, 2 at a time. So, for example, the values of *speed* and *caretaken* for workers ranked first and second would be averaged, and these values assigned to one new worker. The values for the third and fourth ranked workers would then be assigned to a second new worker, and so on. Workers ranked 13 to 44 are allowed to remain in the workforce, but did not pass on their characteristics to any child workers. The new generation of workers thus created was allowed to conduct operations for another 1000 time steps, and the process is repeated, up to a maximum number of generations controlled by the user. This process is the primary vehicle by which management can influence the worker population, with workers farthest from the management value structure being re-educated in the image of workers closest to the management values. Alternatively, it is possible to think of this process as the most valued workers applying peer pressure to least valued workers, but this conceptualization is still fundamentally management driven, because of the application of external weights to the value model.

SIMULATION RESULTS

The results of most interest in this case are the changes in the worker population over time, and the degree to which those changes are influenced by the choice of weights for safe and productive behavior. In fact, the worker population changes rather dramatically based on these choices. Figure 2 depicts the time history of the variable *caretaken* for a range in choices of weights. Figure 3 presents a similar history for the *speed* variable.

On Figure 2, the model indicates that the weighting factors, or the value placed on production versus safety, introduce significant changes in the worker population, other factors being equal. As expected, there is an inverse relationship between *caretaken* and *speed.* As safe performance receives steadily more value, the workers on average pay more attention to safety and move more slowly. The stability of the final equilibrium is highlighted in the *safewt* = 0 model, which is the bottom result on *caretaken* and the top result on *speed.* In generation 14 for this particular iteration, 2 fatal incidents introduce new workers with high degrees of care and attendant slower production. These two have a significant impact on the average speed and care, but are quickly out-competed by more valued, productive workers, and the average returns to its equilibrium level.

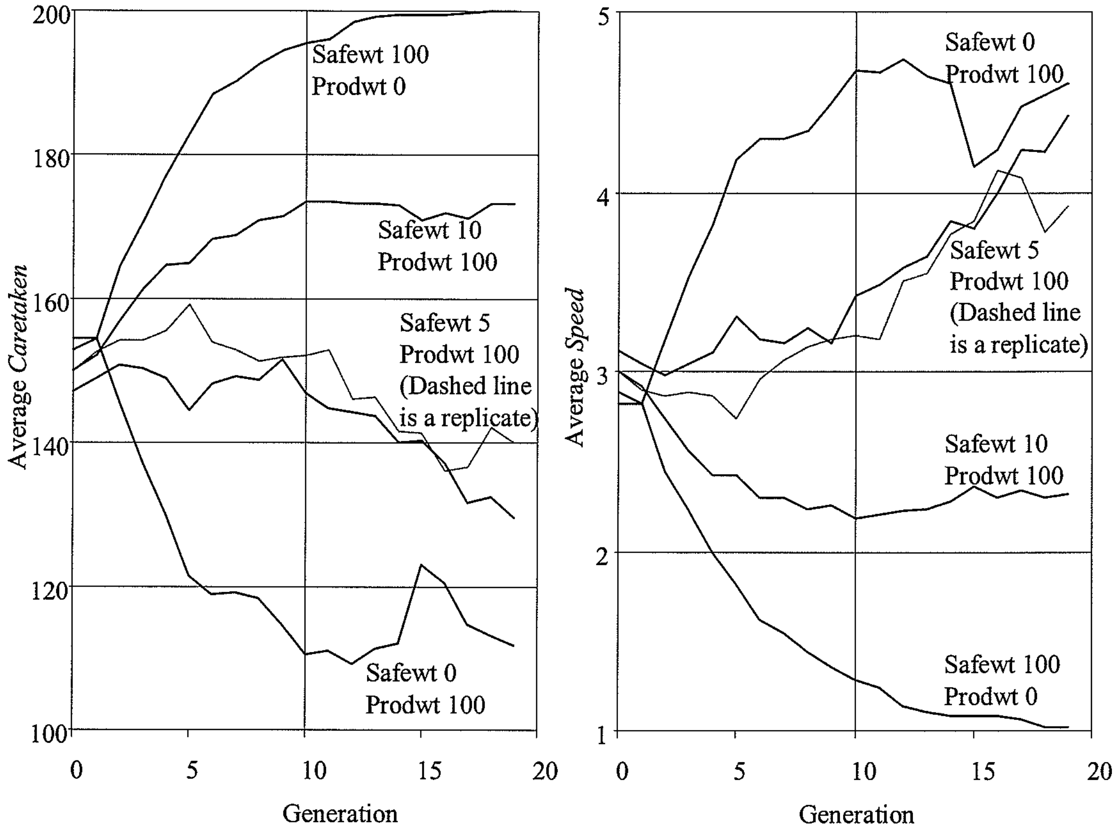

Figure 2: Time History of *Caretaken* and *Speed* for Several Sets of Weights, (average *danger* 100 with standard deviation 50, probability of incident when at risk 25% for all models)

This discussion highlights the issue of the stability and consistency of the results for a given set of weights. The results presented in Figure 2 arise from a single model for each set of weights. To give some idea as to the stability and consistency of the results, a replicate is included for one set of results (the *safewt* = 5 model). In general, the polar models (with either *prodwt* or *safewt* equal to zero) were very consistent and stable. However, models with non-zero values for both weights show somewhat more range. Figure 3 presents 30 iterations for the case with *prodwt* =100 and *safewt* = 7. This model shows that some significant perturbations are present, but the trend is relatively stable. Interestingly, there are multiple solutions when both factors have nonzero weights. Figure 4 shows histograms of the worker population of speed after 50 generations for the *prodwt* =100, *safewt* = 7 case. Note that, while very fast workers are the most common result, in some circumstances the population develops a slower, more careful personality. This solution, while not the most common outcome, seems to occur when a large number of incidents occur early in the replicate history, a circumstance which tends to require several, widely distributed locations with very high *danger*.

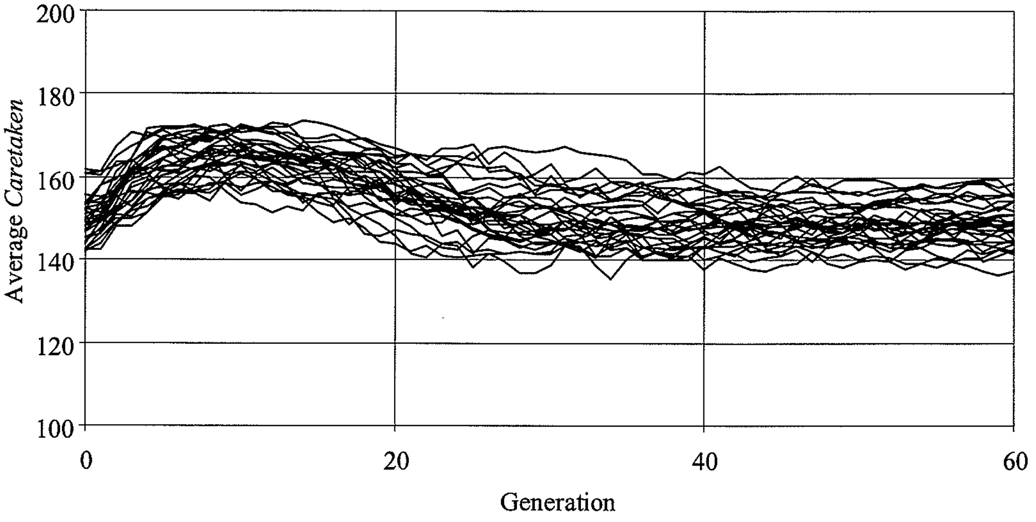

Figure 3:Time History of *Caretaken* for 30 Replicates at *Safewt* = 7, *Prodwt* = 100 (average *danger* 100 with standard deviation 50, probability of incident when at risk 25% for all replicates)

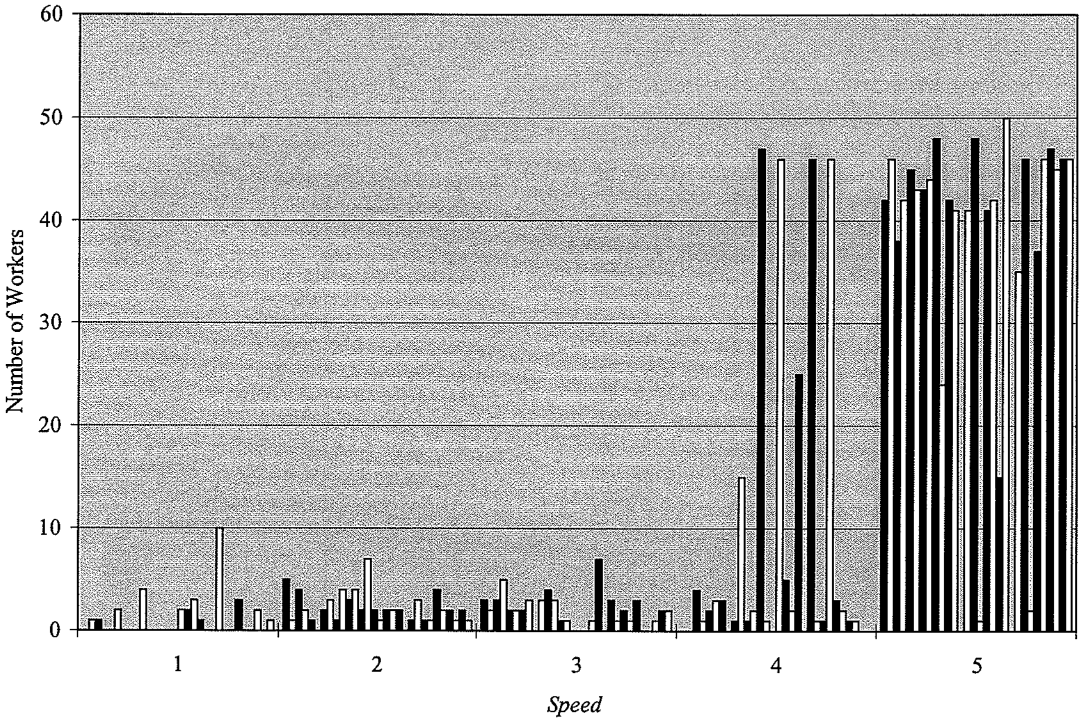

Figure 4: Histogram of Worker *Speed* after 50 Generations for 30 Replicates at *Safewt* = 7, *Prodwt* = 100 (average *danger* 100 with standard deviation 50, probability of incident when at risk 25% for all replicates)

An unexpected outcome of the model is the ability of workers to learn safety behavior beyond the level indicated by the *speed-caretaken* relationship used to develop the initial population. Generation 0 is instantiated with the linear relationship previously described (the line on Figure 5). In early generations, if safety has any weight at all, some high *caretaken* workers will be successful, if only because fast workers have more incidents, and thus a lower score (see equation 1). Because child workers receive an average of *speed* and *caretaken* from high-scoring workers, these high values of *caretaken* often get paired with a fast worker who avoids incidents by virtue of being in a less dangerous area. The child worker thus created is both safe and fast, compared to new workers developed from the linear model, and thus is very successful. This behavior, repeated over many generations, drives the final population toward higher productivity and higher safety performance. Nonetheless, as one can see by comparing Figure 2 and Figure 5, higher weight given to safety produces higher safety performance, even with this learning.

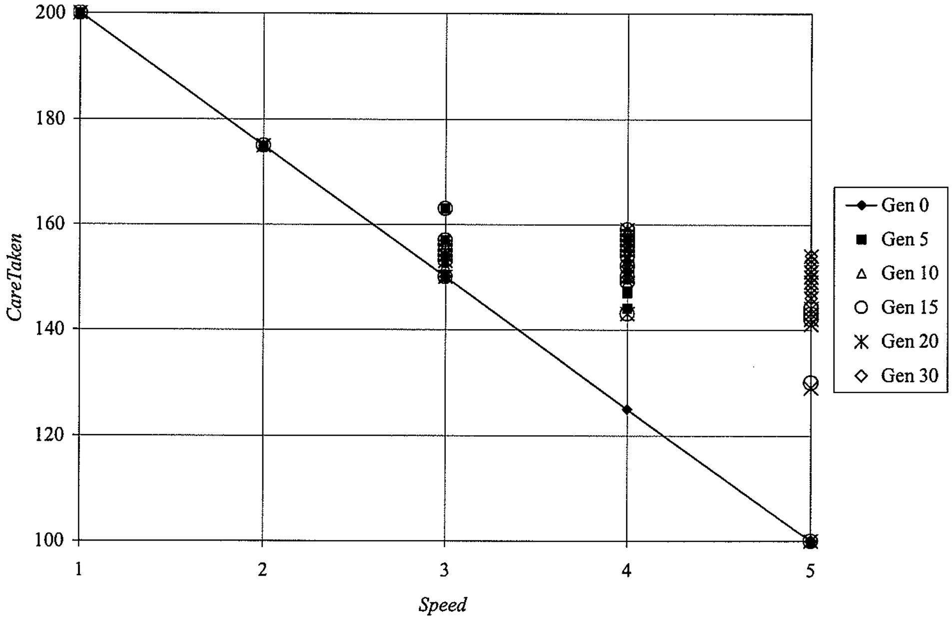

Figure 5: Relationship Between *caretaken* and *speed* at Several Generations for 1 Replicate at *Safewt* = 7, *Prodwt* = 100 (average *danger* 100 with standard deviation 50, probability of incident when at risk 25%)

Perhaps because of this behavior, the long-term average result seems to be independent of the starting worker population. In effect, the same long-term result occurs whether the starting population average *speed* is close to 3, close to 2, or close to 1. Further, if one takes a population of workers from one project, with a given set of weights, and uses them as a starting population for another project with a different set of weights, there is little or no difference between the long-term average result from the “experienced” population and a random population starting with the basic, linear relationship. This implies that, given sufficient time at the project site, the worker population will tend to “forget” past safety culture and respond to the new culture.

CONCLUSIONS

This paper has reported a simple agent-based simulation of worker behavior in response to the safety culture on a site. For this specific model, the productivity of the task is assumed to be strongly influenced by the degree of caution exercised by the worker, and the actions of one worker influence neither the danger level at the site nor the danger facing surrounding workers. The results suggest several interesting relationships.

- This experiment suggests that worker risk-taking behavior is heavily influenced by the degree to which management values safety performance and productivity performance. When management attention is focused on safety, as modeled by the *safewt* = 100 case, workers quickly develop a high level of care. Similarly, when management attention is focused on production only, workers tend to respond by developing high productivity.
- For cases where both safety and productivity performance are valued, the results are intermediate. However, safety performance must receive fairly high value to result in an average level of care demonstrated by workers that exceeds the average plus one standard deviation danger level at the site.
- Safe behavior is encouraged even when management does not highly value safety performance. This result arises from the fact that workers involved in fatal incidents enter the project with only average performance, and are unlikely to excel regardless of the weight given to production. As a consequence, workers in the agent model have an inherent interest in safety, much as they do in reality, even if the underlying motivations may be different. However, improvement in worker care is much faster, and reaches much higher levels, with increasing management value given to safe behavior.

Model assumptions represent a fairly restrictive and idealized case, and will not likely result in simulations of real worker behavior of the sort that one could hope to calibrate against actual safety performance at a particular site. Nonetheless, the results are in general accord with the experiences of the authors, suggesting that the agent-based model may be a promising strategy for understanding behavior-based problems in construction. Several improvements are underway at present, including the use of more complex simulation environments, which would allow the workers to influence each other and the *danger* level at the site more robustly. Further, testing of the sensitivity of the model to changes in the starting level of *danger*, the variability of *danger*, the characteristics of the worker population, and the form of the initial *caretaken-speed* relationship, are underway.

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