Proceedings of the 1999 Winter Simulation Conference
P. A. Farrington, H. B. Nembhard, D. T. Sturrock, and G. W. Evans, eds.

TRAVEL-TIME SIMULATION TO LOCATE AND STAFF TEMPORARY FACILITIES UNDER CHANGING CONSTRUCTION DEMAND

Iris D. Tommelein

Construction Engineering and Management Program
Department of Civil and Environmental Engineering
University of California
Berkeley, CA 94720-1712, U.S.A.

ABSTRACT

Temporary facilities on construction sites are needed to support the labor force during the course of their work. Rules of thumb traditionally have been used to decide on the location and capacity of those facilities, but the demand for support is project dependent and changes as construction progresses at a rate specific to each trade discipline. This paper presents a more systematic method for facility location and capacity sizing based on travel-time simulation. Actual site circumstances, including the location of a temporary facility relative to the location of the workers as well as workers' needs, travel, and service time are taken into account. The objective is to identify the best location on site for temporary facilities on a project-by-project basis. When real-time data becomes available as construction progresses, it can be incorporated in the model to generate even more realistic output. Tool-room location is used as an illustration. The presented simulation model yields data to assess how much travel and wait time is tolerable compared to the cost of increasing the capacity of the support facility or providing service at additional locations.

1 INTRODUCTION

Deciding where to locate temporary facilities such as tool rooms, construction assembly areas, fabrication shops, or warehouses can be done based on rules of thumb, such as "a tool room is needed for every 40 workers on site." However, those rules of thumb do not take into account that the efficiency of operation of the facility is also a function of how easily it can be reached and how fast those requesting services can indeed be served. Many site-specific conditions will affect the demand (e.g., the complexity of the facility being constructed, weather conditions, and site development such as availability of paved roads). Long travel and wait times may result from this situation, which diminish the value of having the temporary facility.

A methodology is presented here that takes into account the location of the temporary facility relative to the location of construction workers, in combination with worker travel and customer service time, in order to help identify the best location on site for that facility. Travel time counts as contributory time: it is incurred out of necessity to support the productive construction process, that is, the process in which materials are actually installed in their final position. However it is not productive time and should therefore be minimized whenever possible.

2 RELATED WORK

In today's construction practice, the sizing for capacity and the layout of temporary facilities on a construction site are usually done based on rules-of-thumb. These rules reflect past experience and may be based on some characterization of the product being built. For instance, Stone&Webster (1979) used the warehouse sizing estimates as shown in Table 1.

Table 1: Warehouse Sizing Estimates for Non-nuclear Power Plants (Stone&Webster 1979)

Single Unit	Non-Nuclear	
MW Rating	Min South	Max North
200	2,000 ft^2	4,000 ft^2
400	4,000 ft^2	8,000 ft^2
600	6,000 ft^2	12,000 ft^2
800	8,000 ft^2	16,000 ft^2
1,000	10,000 ft^2	20,000 ft^2
Two Units	Multiply Total ft^2 x 1.50	
Three Units	Multiply Total ft^2 x 1.75	
Four Units	Multiply Total ft^2 x 2.50	

Tommelein (1989) compiled several other such rules used in industry, all of a similar nature. Obviously they provide only rough, first-order estimates for the needed facilities. They do not take the dynamics of the project into account though planners typically consider stages of construction and plan for growth to peak capacity. In addition, management practices, governing for instance the uncertainty regarding materials delivery rates and the reliability of flows, must also be considered when determining the sizing of temporary facilities. However, uncertainty is often overlooked in practice (e.g., Tommelein et al. 1998) as are matching problems and their impact on flow reliability (Tommelein 1998), even though they do significantly affect the need for and size of temporary facilities (such as the amount of laydown space, warehousing, etc.).

A number of alternative approaches to the layout problem (most of them exclude capacity sizing) are reviewed by Francis, McGinnis, and White (1992) and Tommelein et al. (1992a). In order to allow for a more systematic exploration of solution alternatives, rules have been encoded in knowledge-based systems (e.g, Tommelein et al. 1992b, Cheng and O'Connor 1996). Numerical optimization, heuristic construction and improvement algorithms, as well as neural networks have also been applied to layout planning (e.g., Yeh 1995).

An alternative approach is to use simulation. Simulation provides computational support when determining capacities and locations, provided the needed data sets are available for input (also see 5.3 Discussion). In addition, an interface with a graphical package describing the product as well as layout characteristics (e.g., Odeh 1992, Abourizk and Mather 1998) can lend significant support to the novice user. This makes it easy for the user to interactively add or remove, relocate, or resize the temporary facilities and then study the impact of these changes on the efficiency of the layout.

3 TOOL ROOM LOCATION AND CAPACITY SIZING

The tool-room problem illustrates a location problem that takes variable location, travel, and service time into account. On large industrial construction projects it is customary for the contractor to provide direct-hire, skilled laborers (ironworkers, pipe fitters, electricians, etc.) with some or all of the tools they need to accomplish their work. Not all tools are needed at all times, however. Tools may be expensive to acquire so a significant amount of capital is tied up in them. Damage and theft are issues. Tools may need regular maintenance checks (esp. electrical power tools that are subject to periodic inspection of their wiring) or replacement of consumables (e.g., drill bits, saw blades). Contractors therefore have adopted the practice of issuing tools from a tool trailer on an as-needed basis. Crews have their helpers fetch the needed tools in the course of a day as is necessary to perform their work. Helpers then walk from the work face to the tool trailer, stand in line awaiting service, request and get their tools issued, then return to join their crew.

The location of a tool trailer requires consideration of a multitude of factors: (1) proximity to work areas and demand for tools by workers in each area; (2) availability of temporary power for light and computers in the trailer and computer networking if possible; (3) avoidance of obstruction of other work on site, such as access needed by cranes making large lifts; (4) safe access to and egress from the trailer (e.g., stay away from moving equipment such as rigging equipment and flatbed trailers); and (5) other site specific constraints.

Criteria for tool room sizing and service capacity include: (1) provide tools to meet worker needs; (2) allow for growth with build-up of manpower on site and decline later; (3) recognize one-time setup cost for each trailer added; and (4) staff tool room to keep wait times reasonable. The current industry philosophy for stocking a tool room is that workers should always have access to any tools requested, there should be no tool shortages. Of course, there is no point in carrying too many tools. Not only do they occupy space in the tool room, the contractor also incurs a carrying cost for having those tools available on site.

4 EXAMPLE PROBLEM

Consider a petrochemical project on a site with layout as depicted in Figure 1. This industrial facility comprises two building structures, Unit A and Unit B. Rack 1 supports pipe that connects the units. A tentative location for the double-trailer main tool room and the single-trailer auxiliary tool room were selected manually. They are shown in black with labels Tool Room 1 and 2 in Figure 1.

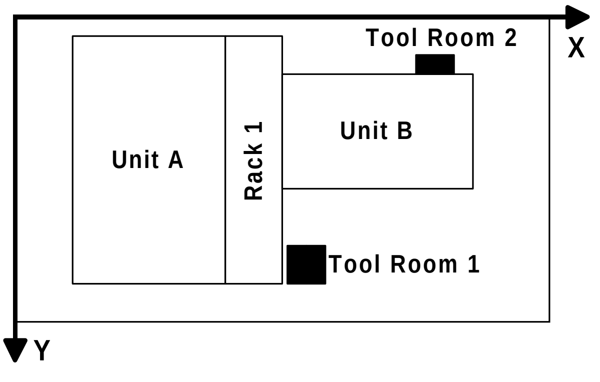

Figure 1: Site Layout of Example Facility
(tool rooms not shown to scale)

This fictitious example is obviously kept simple for illustrative purposes. Extending the model to include more units is straightforward.

The demand for tools changes as construction work progresses. It is a function of the schedule according to which different kinds of work will be performed and also of the number of craftsmen on site for each of the trades. Different trades require different tools.

A simulation model can reflect detailed data on the specific nature of the work being done on a week-by-week basis throughout the duration of the project. If that is not available, it can incorporate data from the overall manpower histograms which here pertain to Unit A, Unit B, and Rack 1 as shown in Figures 2, 3, and 4. These histograms describe the number of craftsmen working at each unit every day; the bars as shown summarize monthly averages.

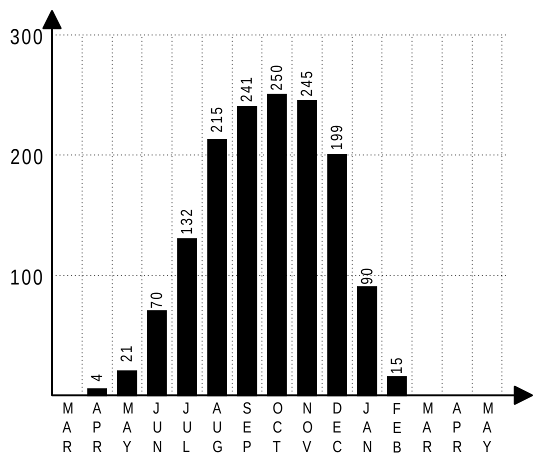

Figure 2: Labor Force Unit A

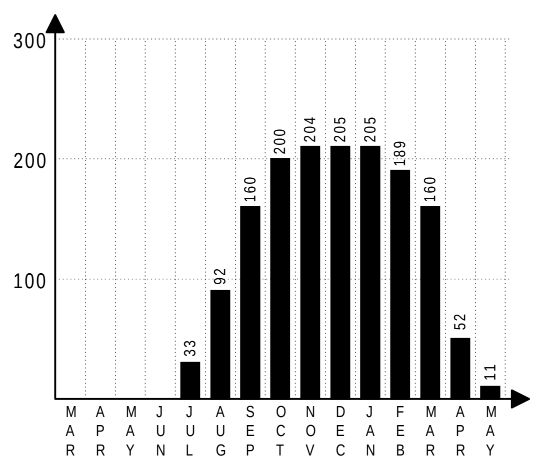

Figure 3: Labor Force Unit B

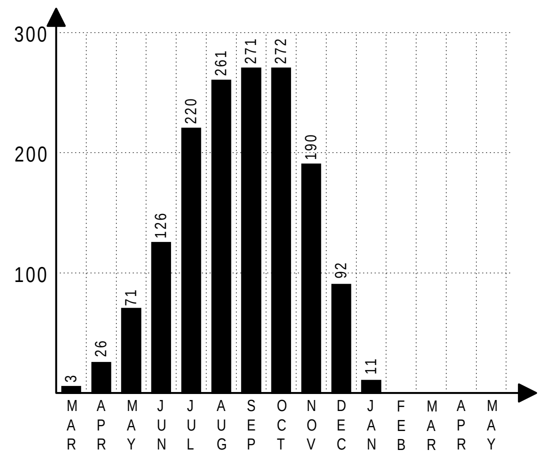

Figure 4: Labor Force Rack 1

5 SIMULATION MODEL

5.1 Modeling Assumptions

The model presented in this paper is based on the following assumptions. (1) On average, 1 helper for 9 skilled workers on site is responsible for fetching tools. (2) Throughout the day each helper makes about 4 round trips to the tool room (one in the morning, three sometime during the day) plus typically 1 one-way trip in the evening to drop off tools prior to brassing out for the day. (3) Travel distance to the tool rooms varies by location of each work crew on any specific day. It is assumed that workers in each unit are distributed evenly over the area that is covered by that unit. This reflects that the focus of work tends to shift from one sub-area in a unit to the next sub-area as work progresses, nevertheless over the duration of construction, work must be done just about everywhere in the unit. Finer division of an area into sub-areas is possible if data is available to support greater detail. (4) A work week comprises five 8-hour days. Upon arrival on site, workers gather in their work area for a safety meeting. Helpers then identify what tools are needed by their crew (this may not take any time: they typically know this at the end of the previous day) and set out to get them. They choose what tool trailer to go to and walk over there. (5) The likelihood of a helper going to one tool trailer or the other is assumed to be inversely proportional to the travel distance to each one. That is, helpers are more likely to go to the trailer closest to their work area, but do not necessarily always do so. (6) Helpers typically follow the shortest path to the tool room. The path more or less follows existing roads (which are orthogonal), as obstructions of all kinds tend to be in the way. (7) While some workers walk faster than others and walking speed depends on the tools they carry, assume some average travel speed. (8) When helpers arrive at the tool room, one of several waiting lines can be joined. Though some lines may serve a different purpose than the others (e.g., issuing of consumables vs. issuing of tools) it is assumed that helpers choose one or the other with equal likelihood. (9) The average transaction involves 2 tools. (10) It is possible for tools to be returned and others to be picked up in the same transaction, but this appears to be seldom the case. A typical round trip is made either to pick up tools or to return tools, not both. (11) The average transaction takes 3 ± 1 minutes to be completed. This includes the tool room clerk taking the order, fetching requested tools and consumables, then scanning the helper's badge and the tools' and consumables' bar codes. Helpers then return to their original work area.

5.2 Implementation

Site layout data relevant to the problem at hand is extracted from the CAD package or site arrangement blueprint. The units and rack as shown in Figure 1 are identified by their position on site. The locations of the manually positioned tool rooms are retrieved as well Gridlines from the site map define the x and y coordinates of the upper left and lower right corner of each rectangle. The x-axis points to the east, the y-axis to the south.

The simulation model for a two tool-room situation is illustrated in Figure 5. QUEUEs (circles with a tail) represent none, one, or several resources waiting to be processed, whereas combination activities (rectangles with a cut-off corner, also called 'COMBIs') represent production tasks that require those resources as input. A circle with a triangle in it denotes a decision node (e.g., after picking up tools, workers choose to return to the area where they came from) or a probabilistic FORK (e.g., workers randomly join one of two waiting lines). A circle with a fan of lines in it is a variant of a fork. It is called a DYNAFORK in the STROBOSCOPE (Martinez 1996) simulation engine that was used to implement this model.

Prior to starting any one task and committing the appropriate resources to it, a decision must be made (not illustrated) on which resources to select first. By default, resources are serviced in a first-in-first-out manner. Activity durations reflect some variation (they are characterized by a probabilistic duration distribution). This way, fluctuations in travel speed, worker location, and service time as may have been observed on site can be mimicked in the computer model.

The model describes the various process steps a craft helper takes when fetching tools. Readers interested in obtaining the source code of this model may contact the author. Only the key parts of the model are described next.

First, a need to get or return tools is identified (GetToolsFor) by a helper who supports a crew. The helper and crew are located in a subarea of A (Unit A), B (Unit B), or C (Rack 1). The crew location changes as work progresses. While abstracting the specifics of their path, but recognizing the variability in their location over time, a point location is used to characterize each helper's work area. This point will be sampled during simulation from a uniform distribution in x- and y-directions, covering the entire area of the unit the helper's crew works in.

Second, the helper must choose which tool room to go to (ChooseTR). Barring specific management instructions for helpers to do otherwise, it is assumed that the likelihood of a helper going to one or the other tool room is inversely proportional to the distance between the helper's work location and the tool room. The distance to each available tool room is calculated in ChooseTR and the corresponding likelihood is encoded in the arrow to the fork BranchToTR, then accounted for in the arrows emanating from it. The helper then walks to the chosen tool room (TravelToTR) and randomly picks a waiting line to join (TRHelperWait). If N waiting lines are available at a given tool room, the model is based on the assumption that the helper has a chance of 1/N to join either one.

After being serviced (TRIssueTools) the worker returns to their crew's work area (ReturnToWork) and joins their crew (SelectUnit). The duration of TravelToTR and ReturnToWork are a function of the distance the helper must travel to get there, assuming an average travel speed of 200 fpm.

Output generated by executing the simulation model reflects system characteristics. For example, the lengths of waiting lines at each of the four tool room windows (three at tool room 1 and one at tool room 2) in the first five hours of a day have been plotted in Figure 6. The area under this curve depicts helper wait time. The associated cost reflects lost helper time but also suggests the possibility that crews may be idle or perform non-planned work while awaiting the tools they need. The total travel time of helpers to and from the tool rooms and the time tool room clerks are idle can also be assessed. A user can thus explore the cost associated with a chosen tool room configuration.

The largest demand for tools occurs during the morning rush. This creates the greatest bottleneck: workers will have to wait before they can check out their tools at the trailer. In practice, another rush may occur right after lunch and when site work shuts down in the evening, though these have not been modeled here. Tool rooms are likely to be staffed with more personnel during these rush hours than they are for the rest of the day.

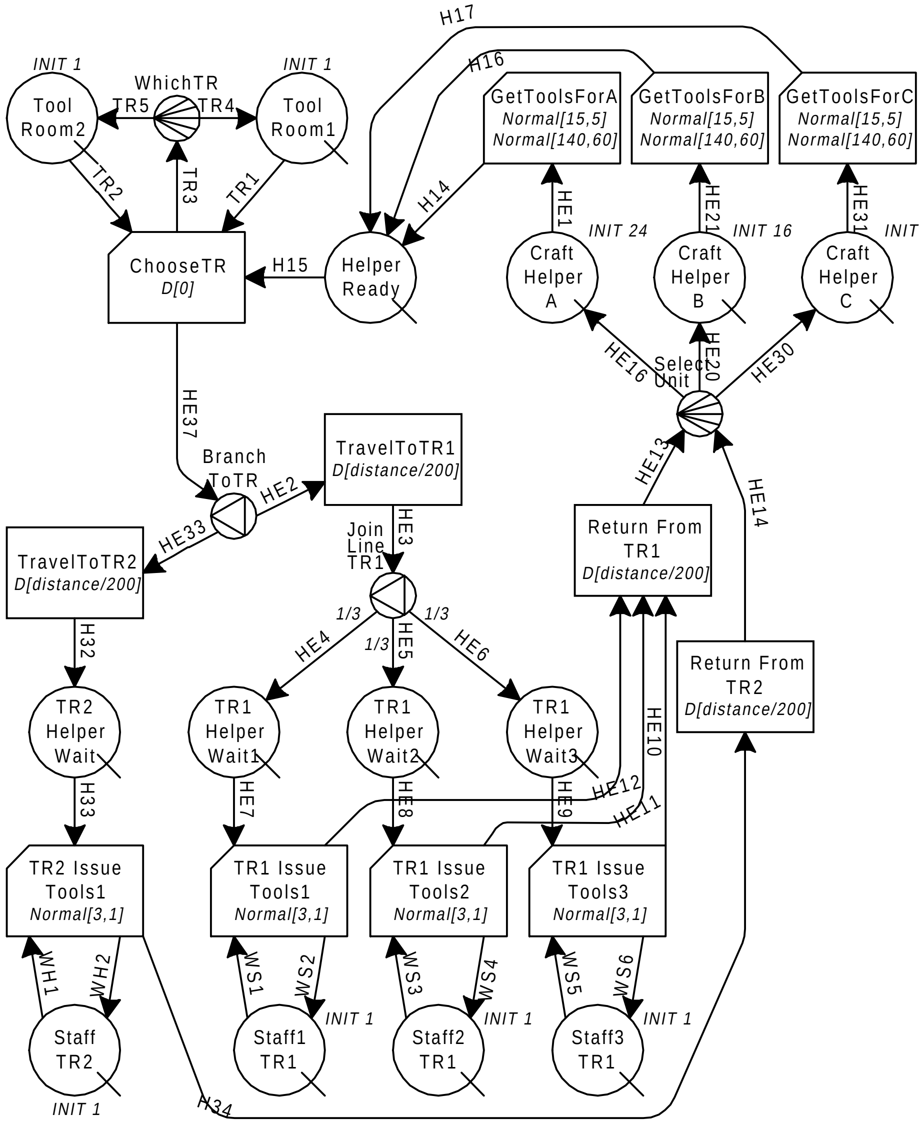

Figure 5: Simulation Model for Tool Room Problem

5.3 Discussion

Obviously, a different tool room configuration will yield different results. Prohibitively slow waiting lines or large travel distances can be shortened by changing the configuration. Using the model, one can experiment with alternative locations of a given number of tools rooms, a different number of tool rooms each requiring a mobilization and demobilization cost, and different tool room staffing throughout the day. Simulation output for each alternative will help determine which configuration is most favorable based on the manpower on site and location of work throughout the duration of the project.

While figure 6 charted the output of a single iteration of the simulation using data for the month of September, multiple simulation runs for each month will yield data necessary to compute statistically significant averages and variation coefficients. The model can simulate a single day’s operation or a longer time span.

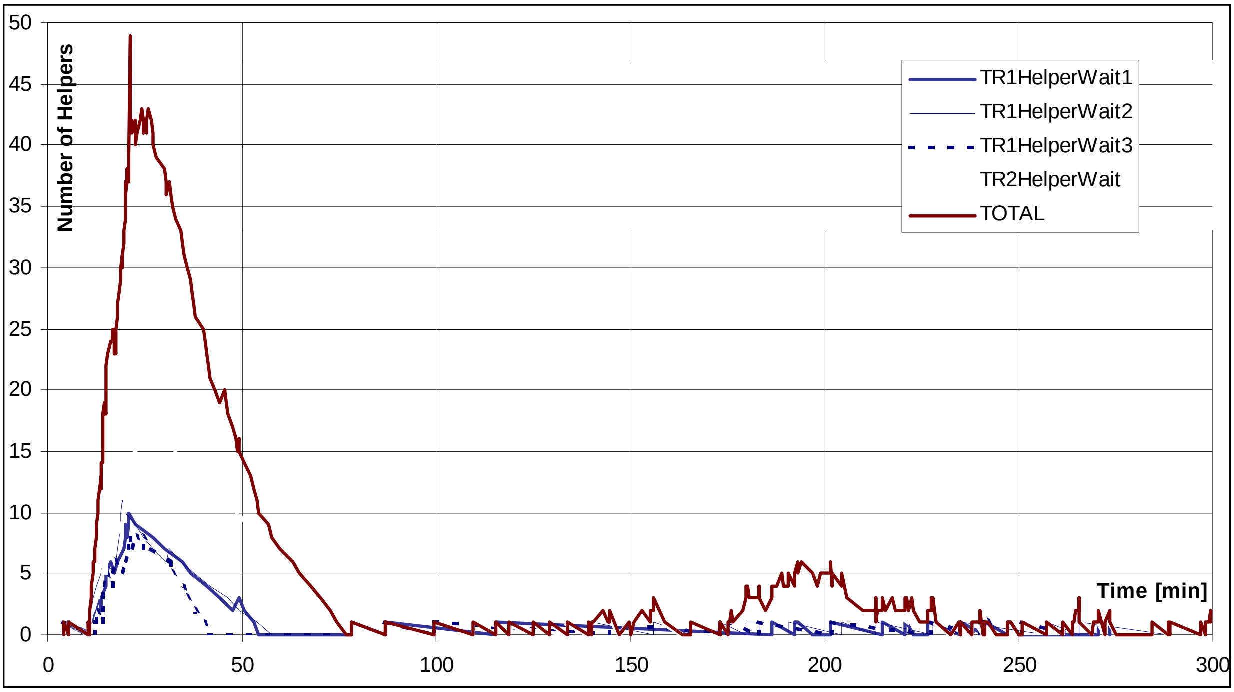

Figure 6: Length of Waiting Lines at Four Tool Rooms

The number of helpers initialized in the queues CraftHelper can reflect manpower histograms such as those depicted in Figures 2, 3, and 4. This may be programmed in STROBOSCOPE, for instance, using an array showing the month vs. the number of workers on site. During the simulation, the appropriate queues must then be reinitialized each month. The simulation will thus take into account that the geographic distribution of the demand for tools varies in the course of a project because unit construction tends to be phased in order to avoid—at least to some extent—peak demands for resources. Similarly, variation in staffing of tool rooms during the day can be incorporated by associating a work schedule to the staff available in the StaffTR queues.

The power of the method described here is that it can take into account the actual circumstances at the site where work takes place. Many large contractors today are using sophisticated inventory control programs that can easily generate the data needed to support simulation modeling. Issuing and tracking individual tools is made easy by the use of computer-based bar coding systems. Tools are tagged with bar codes and helpers have identification badges that are also bar coded. Simulation thus becomes practical where management previously had no data and thus could use only rules-of-thumb.

A preliminary simulation model can be developed at the project planning stage using historic tool-issuing data, anticipated manpower histograms, and a project's site layout. As work progresses and the construction schedule gets changed or new site constraints are identified, the requirements for tools may change. The simulation can then be run again using tool inventory data collected for the project at hand, to see if additional facilities are needed, facilities should be relocated or removed, or staffing should change.

The model depicted in Figure 5 was hand-coded. However, the STROBOSCOPE simulation engine is programmable so the tool-room model can be parameterized in order to scale according to problem specifications (Ioannou and Martinez 1996). This will be necessary when the graphical front-end gets developed to interactively change layouts.

6 SUMMARY

A simulation model was presented to investigate the amount of time construction workers spend travelling and waiting to get service at a temporary facility. Travel time is incurred by workers or equipment moving from one location to another. This is the case, for instance, for craft helpers fetching tools at the tool room; workers arriving and departing from site, traveling from the parking area, through the site gate, to their work area; workers retreating to lunch tents during breaks; and expediters moving materials from a laydown yard to a staging location near the work face.

As was illustrated in this paper, simulation makes it possible to mimic the variability so typical of workers going from their work area to the tool room, waiting in line for tools to get issued, then returning to their work area. A computer simulation model was developed that reflects the spatial distribution of construction workers on site, defining their selection of a support facility to get serviced by as well as their travel time to and from it, and thus their random arrival times. This model makes it possible to locate and size support facilities in order to best meet demand.

ACKNOWLEDGMENTS

Simulation is an essential tool in Iris Tommelein's research into improving construction materials management and site logistics. The presented work was funded by grant CMS-9622308 from the National Science Foundation, whose support is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

AbouRizk, S. and K. Mather 1998. A CAD-Based Simulation Tool for Earthmoving Construction Method Selection. ASCE, *Proc. Computing in Civil Engrg*. 39-52.

Cheng, M.Y. and J.T. O'Connor. 1996. ArcSite: Enhanced GIS for Construction Site Layout. *J. of Constr. Engrg. and Mgmt*., ASCE, 122:4, 329-336.

Francis, R.L., L.F. McGinnis Jr., and J.A. White. 1992. *Facility Layout and Location: An Analytical Approach*. Prentice-Hall, Englewood Cliffs, New Jersey, 589 pp.

Ioannou, P.G. and J.C. Martinez. 1996. Scaleable Simulation Models for Construction Operations. In *1996 Winter Simulation Conference Proceedings*. Institute of Electrical and Electronics Engineers, Piscataway, New Jersey, 1329-1336.

Martinez, J.C. 1996. *STROBOSCOPE State and Resource Based Simulation of Construction Processes.* Ph.D. Dissertation, Civil & Envir. Engrg. Dept., Univ. of Michigan, Ann Arbor, Michigan, 518 pp., available at http://www.strobos.ce.vt.edu/.

Odeh, A.M. 1992. *CIPROS: Knowledge-based Construction Integrated Project and Process Planning Simulation System*. Ph.D. Dissertation, Civil and Envir. Engrg. Dept., University of Michigan, Ann Arbor, Michigan.

Stone&Webster 1979. *Construction Field Manual—Construction Facilities Guidelines, Volume I*. Construction Department, CFG 2.2, Rev. 0, 8 pages, Stone&Webster Engineering Corporation, Boston, Mass., 23 March 1979.

Tommelein, I.D. 1989. *SightPlan—An Expert System that Models and Augments Human Decision-Making for Designing Construction Site Layouts.* Ph.D. Dissertation, Department of Civil Engineering, Stanford University, Stanford, CA, August; hard copy available from University Microfilms.

Tommelein, I.D. 1998. Pull-driven Scheduling for Pipe-Spool Installation: Simulation of Lean Construction Technique. ASCE, *J. of Constr. Engrg. and Mgmt.* 124:4, 279-288.

Tommelein, I.D., R.E. Levitt, and B. Hayes-Roth. 1992a. Site Layout Modeling: How Can Artificial Intelligence Help? ASCE, *J. of Constr. Engrg. and Mgmt.* 118:3, 594-611.

Tommelein, I.D., R.E. Levitt, and B. Hayes-Roth. 1992b. SightPlan Model for Site Layout. ASCE, *J. of Constr. Engrg. and Mgmt.* 118:4, 749-766.

Tommelein, I.D., D. Riley, and G.A. Howell 1998. Parade Game: Impact of Work Flow Variability on Succeeding Trade Performance. *Proc. Sixth Annual Conf. International Group for Lean Construction*, IGLC-6, 13-15 August held in Guaruja, Brazil, 14 pp.

Yeh, I.C. 1995. Construction-Site Layout Using Annealed Neural Network. *J. of Comp. in Civil Engrg.*, ASCE, 9:3, 201-208.

AUTHOR BIOGRAPHY

IRIS D. TOMMELEIN is an Associate Professor of Construction Engineering and Management in the Civil and Environmental Engineering Department at the University of California, Berkeley. Her research interest is in developing principles of production management for the architecture-engineering-construction industry, what is termed 'lean construction.' Her research focuses on the work specialty contractors perform and how they can become integral participants in design-build teams in order to increase process and product development performance.

Professor Tommelein is an expert on construction site logistics, layout, as well as materials and supply-chain management. Her work involves computer-aided design, planning, scheduling, simulation, and visualization of construction processes; wireless communication, bar coding, and laser-based positioning.