PARADE GAME: IMPACT OF WORK FLOW VARIABILITY ON TRADE PERFORMANCE

By Iris D. Tommelein,[1] David R. Riley,[2] and Greg A. Howell[3]

ABSTRACT: The Parade Game illustrates the impact work flow variability has on the performance of construction trades and their successors. The game consists of simulating a construction process in which resources produced by one trade are prerequisite to work performed by the next trade. Production-level detail, describing resources being passed from one trade to the next, illustrates that throughput will be reduced, project completion delayed, and waste increased by variations in flow. The game shows that it is possible to reduce waste and shorten project duration by reducing the variability in work flow between trades. Basic production management concepts are thus applied to construction management. They highlight two shortcomings of using the critical-path method for field-level planning: The critical-path method makes modeling the dependence of ongoing activities between trades or with operations unwieldy and it does not explicitly represent variability. The Parade Game can be played in a classroom setting either by hand or using a computer. Computer simulation enables students to experiment with numerous alternatives to sharpen their intuition regarding variability, process throughput, buffers, productivity, and crew sizing. Managers interested in schedule compression will benefit from understanding work flow variability's impact on succeeding trade performance.

INTRODUCTION

Lean thinking (Womack and Jones 1996) recognizes variability and the devastating impact it has on the continuous flow of work as well as the resulting throughput of a system. Accordingly, one of its tenets is to synchronize and physically align all steps in the production process, so there is little wait time for people or machines, and virtually no staging of materials or partially completed products. This sounds straightforward enough, except that few people have a good intuitive understanding of how variability really affects the flow of work.

Work flow can be characterized in different ways. In manufacturing, it is defined by partially completed products being transported from one stationary machine to the next. In construction, the products being built tend to be stationary, whereas crews of various trades move from location to location and complete work that is prerequisite to starting work by the following crew. There are obvious similarities and differences between manufacturing and construction, as many have argued before. Both can nonetheless be viewed as production systems including processing stations (machines or crews) and hand-offs of partially completed work. Production principles developed for manufacturing systems therefore also apply to construction.

To enhance intuitive understanding of the impact variability has on work flow, the writers describe the simplest of all production systems, namely a single line of processing stations where products output by one are input required by the next one. Building construction practice reveals the existence of many such single-line production systems, termed here as ''parades of trades.'' A better understanding of these systems can be gained by means of simulation games, to be played manually or using a computer. Such games reveal the general lack of project management understanding and the absence of tools for managing the parade.

PARADE OF TRADES IN BUILDING CONSTRUCTION PRACTICE

Building construction involves a large number of specialty trades that generally work in a continuing and repeating sequence as they move from one floor to another. Specialty trades typically work as subcontractors to the general contractor and may include those responsible for the building's foundation, steel erection, decking, formwork, concrete reinforcing bars, concrete, drywall, mechanical, electrical, plumbing, roofing, glazing, vertical transportation systems, fire protection systems, environment controls, to name but a few. Gus Sestrup, superintendent with Turner Construction, says these contractors' work sequences should be performed as a ''parade of trades.'' Example parades are (Riley and Sanvido 1997) as follows:

- Structural Parade: e.g., erecting structural steel (steel erector); placing and securing decking as well as welding shear studs (decking contractor); and placing rebar (rebar contractor), then pouring and finishing concrete (concrete contractor).
- Overhead Work Parade: e.g., installing a HVAC system (mechanical contractor), sprinkler system (fire protection contractor), emergency lighting (electrical contractor), and pipe (plumbing contractor).
- Perimeter Enclosure Parade: e.g., building perimeter walls, placing windows, installing flashing, and applying sealants.
- Interior Finishes Parade: e.g., installing wall studs, routing electrical conduit, placing insulation materials, hanging drywall, and painting.

Gravity-supported systems, typified by the structural parade, tend to follow a strict sequence. It is also preferable to install gravity plumbing systems and HVAC duct before pressured piping systems with hot and cold water, in turn followed by electrical conduit. Of course, if the installation of one system blocks access for the installation of another, then the latter system should go in first. Sequencing tends to be more important in highly congested areas and less so in areas with

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[1] Assoc. Prof., Civ. and Envir. Engrg. Dept., 215-A McLaughlin Hall, Univ. of California, Berkeley, CA 94720-1712. E-mail: tommelein@ce.berkeley.edu

[2] Asst. Prof., Dept. of Constr. Mgmt., 116 Architecture Hall, College of Architecture, Univ. of Washington, Seattle, WA. 98195-1610. E-mail: driley@u.washington.edu

[3] Adjunct Prof., Boise State Univ., Boise, ID 83707, and Virginia Polytechnic Inst. and State Univ., Blacksburg, VA 24061, and Executive Dir. of the Lean Construction Inst., Box 1003, Ketchum, ID 83340. E-mail: ghowell@micron.net

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easy access. Access, enclosure, support, etc., all are important determinants of precedence (Gray 1986). Similarly, reciprocal dependencies must be identified early as they may force one trade to perform only a portion of their work, then leave and return when subsequent trades have completed prerequisite work (Riley and Sanvido 1997).

When assigning work to crews, it is also important to recognize the extent to which the concentration of work varies by trade throughout the building. If a preceding trade enters an area with a lot of work specific to their trade, thereby taking a longer time to complete than the moving parade can tolerate, successors may have to get out of line and perform out-of-sequence work elsewhere. Relocation takes extra time, but it may prevent the crew from becoming idle altogether. Out-of-sequence installation for one trade does not necessarily impede other trades' work.

Finally, different parades move through a building in different directions. Riley and Sanvido (1995) distinguished the work area, prefabrication area, storage area, and product-space patterns to characterize the space behavior of various trades. This crisscrossing of parades makes managing them an even bigger challenge.

The existence of parades of trades is widely recognized—though probably not under this name—by superintendents who coordinate the work of specialty contractors. Construction work is often scheduled accordingly. However, to expedite project completion, general contractors may compress the project schedule and force succeeding trades to follow on their predecessor's heels. This may jeopardize the succeeding trades' ability to perform—especially when the performance of one or more predecessors is unreliable, that is, when output varies considerably from one day to the next, and when this output is prerequisite to the work done by the successor. To enable the parade to expedite job completion and minimize waste (in terms of crew idle time or remobilization effort), it is essential that work be released reliably between the trades.

The rate of progress of an activity is often quoted by means of a single number as in ''We plan to erect 80 steel components per day.'' Even though all trades may plan to proceed at the same pace, each trade's production rate alone is insufficient to gauge the speed of the parade as a whole. The single number only represents an average and the actual production rate will vary (e.g., with some standard deviation if a Normal distribution appropriately characterizes variation) because of variation in the weight and size of components, ease of reach and access to their final installation location, fabrication and erection tolerances, skill level of the workers, etc. This deviation from a mean value represents what we here term ''variability.'' ''No variability'' means production is ''reliable.''

Superintendents often express their desire for or the importance of reliability with ''rhythm'' as in ''We just can't seem to get a rhythm on this job.'' Rhythm serves as a substitute for reliability, but is misleading in that it can suggest the problem is in each trade rather than a design feature of the production system. From a production system standpoint, a greater average rate is not beneficial to the system if it comes at the expense of reliability. The Parade Game illustrates the impact variability has on the production rates of trades that succeed one another in a linear sequence.

UNDERLYING THEORETICAL ISSUES

Determining which parades are best suited where and when so that the project can be completed expediently is a production management task, typically handled by construction superintendents. While they may appear to be effective at managing the parade, regrettably, their goal is not necessarily to accommodate the planned productivity rates of all trades involved. Superintendents may favor one trade or building system that is perceived to be a priority (usually the structural system), thereby often causing other trades to suffer productivity losses. Worse, their focus on reducing cost or speeding any one activity can easily destroy the performance of the production system as a whole.

In addition to superintendents, project managers also need to understand the complexity of the production system together with its various performance characteristics, so that they will impose reasonable demands when selecting and managing those performing the work and recognize the real culprit when problems occur. Project management training, however, tends to focus on managing contracts and projects, not on managing production. Consequently, managers often end up imposing unrealistic expectations on the production process or fail to manage it altogether (Tommelein and Ballard 1997).

Project management schedules that use the critical-path method (CPM) describe activities with their durations and precedence relationships. The finish-to-start relationship is most often used, though it assumes sequential finality, i.e., predecessors must be 100% complete before their successors can start. This assumption certainly does not hold in the parade of trades where regular hand-offs exist between trades, and once the parade has started, all trades have to move in sync for the parade to progress at a steady pace. The CPM schedule's misrepresentation of the parade is the key reason why most superintendents use it only as a loose guide for executing work. Many project managers call CPM a critical planning and coordination tool, but admit that ''the super will run the job the way he wants to.'' Other production variables and performance characteristics must therefore be used to describe the parade of trades. They are defined as follows:

- Production Capacity: number of trade-specific work units per unit of time a crew is technically able to finish provided their work is unconstrained (i.e., directives, materials, tools, equipment, crew, work space and suitable environmental conditions, and prerequisite work are available as needed).
- Production Rate: actual number of trade-specific work units per unit of time a crew is able to finish given constraints on their work (e.g., lack of prerequisite work completed, nonavailability of materials, or impeded work space).
- Buffer: work units accumulated ahead of a crew, from which they can draw at will to perform work.
- Wasted Time: time during which a crew is not able to realize its production capacity due to constraints that hamper their work, which results in lost productivity.
- Project Duration: time it takes from start to completion of a project.
- Throughput: number of work units completed divided by the project duration.

PLAYING THE PARADE GAME

Game Description

The game that is presented in this paper was inspired by Goldratt's ''boy-scout hike'' (Goldratt and Cox 1986). By analogy, Greg Howell developed a game that is easy to play with students in a classroom situation. The game can involve any number of players. The game coordinator will split up large groups in teams of equal size, e.g., five players each. Each team forms a parade of trades with players lining up in sequence. Each player represents a subcontractor's crew, as is illustrated by the symbols Crew A through Crew E in Fig. 1 (readers familiar with symbols used in discrete-event simulation will recognize the queues and combination activities). Each crew is to perform an activity that requires the repeated

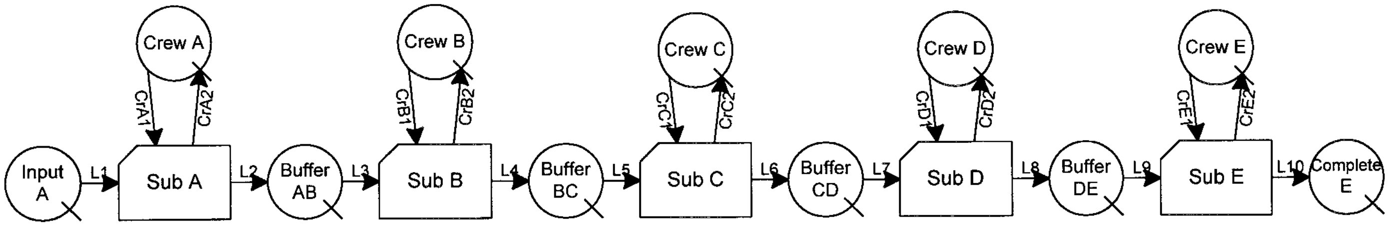

FIG. 1. Parade of Trades Line-Up

TABLE 1. Variability of Available Dice

Type of die (1)	Numbers on faces (2)
A	5, 5, 5, 5, 5, 5
B	4, 4, 4, 6, 6, 6
C	3, 3, 3, 7, 7, 7
D	2, 2, 2, 8, 8, 8
E	1, 1, 1, 9, 9, 9

execution of a process step, for instance, Crew A will repeatedly execute step Sub A. Each team is given a pile of 100 bolts (or any other kind of widget) and their task is to pass them all from the front of the line (the input buffer, Input A) to the end (the output buffer, Complete E). When this has been accomplished, the project is completed.

Each player in line can pass only a limited number of bolts from one side to the other (e.g., Sub A will move them from Input A to Buffer AB) as the number moved is determined by rolling a die. At the beginning of the game, the coordinator will hand each team one of five possible dies, A, B, C, D, or E. After a player has rolled the die and passed the appropriate number of bolts, that player must wait until the next player downstream in turn has rolled the die and taken bolts from the buffer in-between them, before replenishing this buffer. (It may be easier at first to give only one die to each team and have the players pass it down the line to enforce the discipline of the sequence, but this extends the duration of the game.)

The coordinator can introduce various degrees of variability in the game by writing made-up numbers on each face of each die. This is done prior to handing dice to players. A normal die has faces with values 1, 2, 3, 4, 5, and 6, and so the average roll is 3.5. The writers suggest that the game be played with several different dice as described in Table 1, each however having an average roll of 5. From an ''average production'' viewpoint, the dice are therefore identical. When variability is considered, they clearly are not.

Instead of allowing each player to choose their own die, the coordinator may wish to provide all players in one team with dice of type A (all-5), a second team with dice of type C (3-7 dice), and another team with dice of type E (1-9 dice), etc. (It may also be worthwhile to have one team use dice with a higher average roll and a wide distribution. Results are reported later in this paper for a team using dice with an average roll of 7 and a distribution ranging from 3 to 11.)

Each time a player rolls the die, that player should record [1] the number rolled and [2] the number of bolts that could be drawn from the buffer immediately upstream. If the upstream buffer is smaller than the number rolled, that smaller number is the number of bolts passed along. Alternatively, the players can plot on transparencies their number of rolls relative to cumulative production (the total number of bolts they passed along, as shown later in Figs. 2–5) and then overlay them to understand the effect of variability on performance within the team. When all 100 bolts have been passed to the end of the line, the team has completed its task. Each player then calculates [3] the average of the numbers written on the die, [4] the number of times the player rolled the die, [5] the total of all numbers rolled, [6] the average number rolled by dividing [5] by [4], [7] the average number of bolts passed along by dividing 100 by [4]. The team's project completion time under these rules is equal to the number of rolls of the last player in the line plus the total number of players minus one.

Items for Group Discussion

When all teams have completed their project, the group should discuss its findings. Issues to inquire about fall into two categories: (1) Data analysis and (2) reflections on real life.

Data Analysis

- Which team completed their project in the shortest amount of time? Could this have been anticipated, given the dice provided to them? Note that since this game is governed by randomness, the actual outcome is likely to differ from the expected outcome.
- What may cause the number available to draw [2] to be less than the number rolled [1]? The cause is that the player upstream rolled a low number and was unable to provide much of a supply. The player downstream then is said to ''starve'' due to lack of resources. Similarly, when the player upstream rolls a large number and the player downstream rolls a small one, bolts will accumulate in a buffer between them.
- What is the relationship between the average number passed along [7] and the average of numbers written on the die [3]? How do these numbers compare for the various players relative to their position in the production line?
- What is the relationship between the average number rolled [6] and the average of numbers written on the die [3]?
- If you wanted to be certain to get the project done in 24 time units, what dice would you give to the team?
- Which team may have a chance of getting the project done in less than 20 time units?
- What does it mean when the average number passed along [7] is smaller than the average number rolled [6]?
- If a team is playing with dice that have a variability of plus-or-minus 4 relative to their average roll, how can one increase the likelihood that the team will complete its project in as much time as the all-5 team? That is, how can one make an unreliable team speed up?

Reflections on Real Life

- How does this game relate to reality? Can you find examples in construction or other areas? For instance, traffic on a freeway is a good example that raises many similar issues.
- Which trades come early in the parade and which at the end?

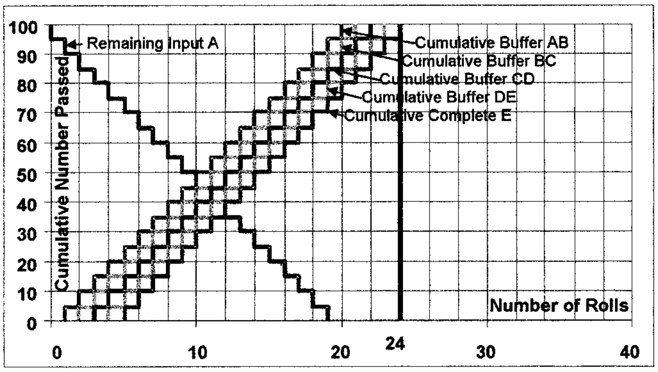

FIG. 2. Output from Single-Iteration Simulation Where All Players Have Die A (All-5)

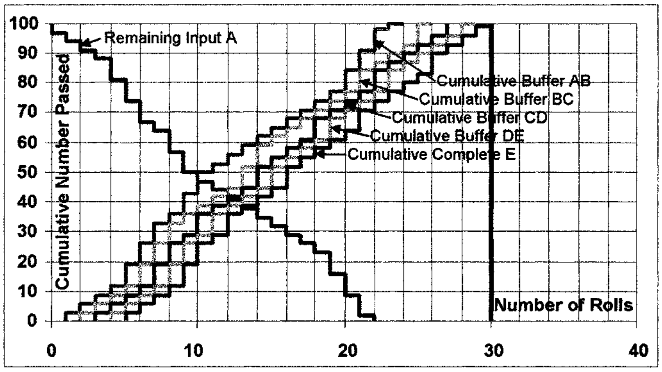

FIG. 3. Output from Single-Iteration Simulation Where All Players Have Die C (3-7)

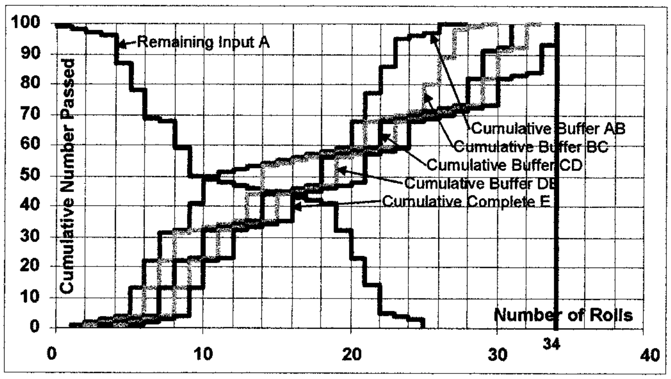

FIG. 4. Output from Single-Iteration Simulation Where All Players Have Die E (1-9)

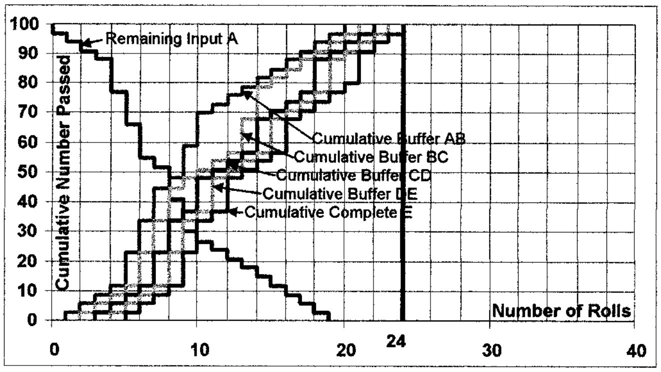

FIG. 5. Output from Single-Iteration Simulation Where All Players Have Die with Increased Average Roll of 7 (3-11)

- What would you do if you were a subcontractor facing the situation of position 5 (Sub E) in the game?
- Given the choice of a more reliable crew or one with a higher average production rate, which one would you choose if you were the crew foreman working for the subcontractor? If you were the project manager working for the general contractor? Why?
- What information about the performance of the team is provided by cost or production data at any one position?
- Because upstream variation affects downstream performance, should downstream positions offer pay for higher reliability upstream?
- What controls work flow on a project? How might you manage your project to avoid or minimize the combined effects of variation and dependence?

COMPUTER SIMULATION OF PARADE OF TRADES

The Parade Game can be played with any type of die. For illustrative purposes, a few combinations were investigated further using computer simulation. Four alternatives are depicted in Figs. 2–5. Each figure in this first set illustrates what the cumulative number of bolts passed may be when the game is played once. Of course, given the randomness in the outcome of a die at each roll, the plots will look different with each repetition of the game. In Fig. 2, all players have an all-5 die. In Fig. 3, all players have a 3-7 die. In Fig. 4, all players have a 1-9 die. Finally, in Fig. 5, all players have a ‘‘faster’’

TABLE 2. Output Values for Single-Iteration Simulations

Process step (1)	First start (2)	Last finish (3)	Actual number of rolls (4)	Average actual roll (5)	Average number of units passed (6)
			(*a*) All-5 Die		
Sub A	0	20	20	5	= actual
Sub B	1	21	20	5	= actual
Sub C	2	22	20	5	= actual
Sub D	3	23	20	5	= actual
Sub E	4	24	20	5	= actual
			(*b*) 1-7 Die		
Sub A	0	23	23	4.57	4.35[a]
Sub B	1	25	24	4.33	4.17
Sub C	2	27	25	5.08	4.00
Sub D	3	28	25	6.02	4.00
Sub E	4	30	26	5.46	3.85
			(*c*) 1-9 Die		
Sub A	0	26	26	4.08	3.85
Sub B	1	29	28	3.86	3.57
Sub C	2	31	29	5.14	3.45
Sub D	3	32	29	6.79	3.45
Sub E	4	34	30	6.60	3.33
			(*d*) 3-11 Die		
Sub A	0	20	20	5.40	5.00[b]
Sub B	1	21	20	5.80	5.00
Sub C	2	22	20	7.80	5.00
Sub D	3	23	20	9.40	5.00
Sub E	4	24	20	8.60	5.00

[a] Even the first person in line may have an average number of units passed less than its average actual roll because starvation can occur when the input buffer is near depletion.

[b] It was pure coincidence that this iteration yielded a 5 for the average number of units passed. These five bolts, which are passed along by the first person in line, get passed along downstream as well, as each station had excess capacity: Actual rolls always ended up being larger than the size of the upstream buffer. Had any one player rolled a low number, resulting in a buffer of only 3, downstream player performance would have been constrained by that.

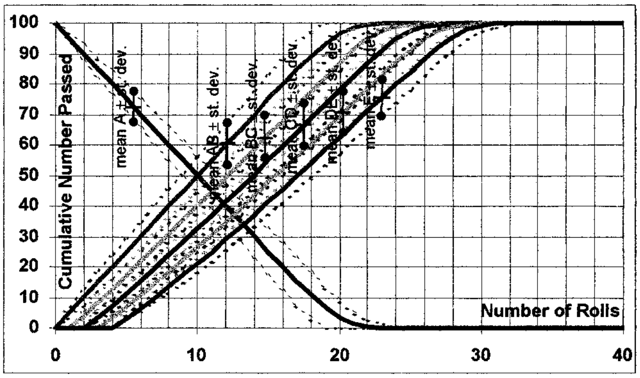

FIG. 6. Output from 1,000-Iteration Simulation Where All Players Have Die C (3-7)

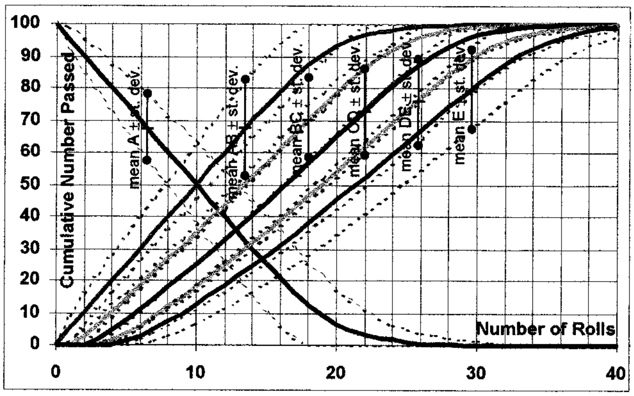

FIG. 7. Output from 1,000-Iteration Simulation Where All Players Have Die E (1-9)

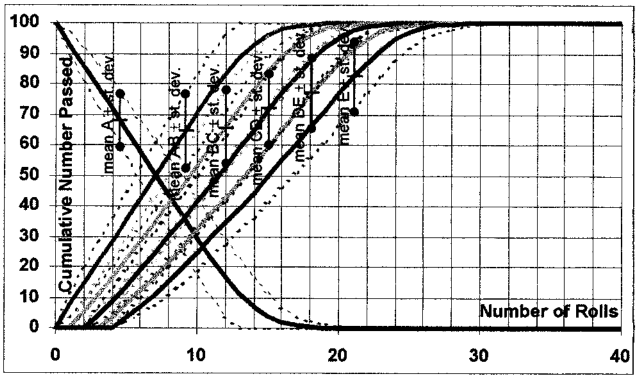

FIG. 8. Output from 1,000-Iteration Simulation Where All Players Have Fast Die (3-11)

die, with an average roll of 7 instead of 5 (numbers on faces are 3, 3, 3, 11, 11, 11). The all-5 project took 24 rolls to complete, the 1-7 project 30, the 1-9 project 34, and the 3-11 project 24.

After comparing these plots, the reader can draw their own conclusions regarding the impact of variability on succeeding trade performance, and especially on project completion and system throughput. Note that the slopes of the cumulative number passed diminishes for more downstream stations in each model. Unfortunately, those farther down the line are subjected to the variability in output provided by those upstream.

Simulation data for each of these models are given in Table 2. Column (1) designates each process step. The table is divided in sections based on the die used in each alternative. Assuming each roll of the die takes a unit time of 1, column

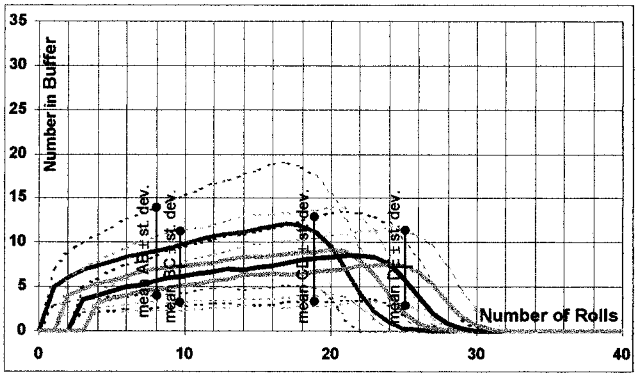

FIG. 9. Buffer Size from 1,000-Iteration Simulation Where All Players Have Die C (3-7)

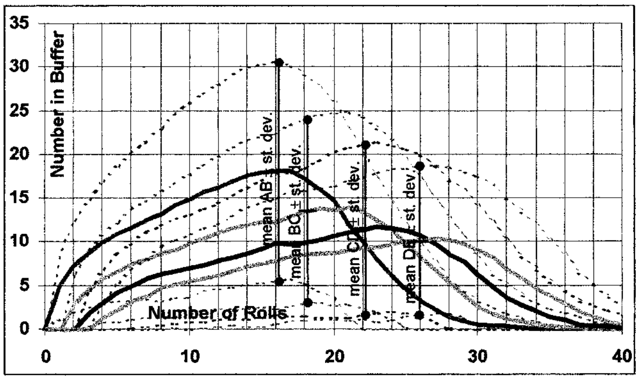

FIG. 10. Buffer Size from 1,000-Iteration Simulation Where All Players Have Die E (1-9)

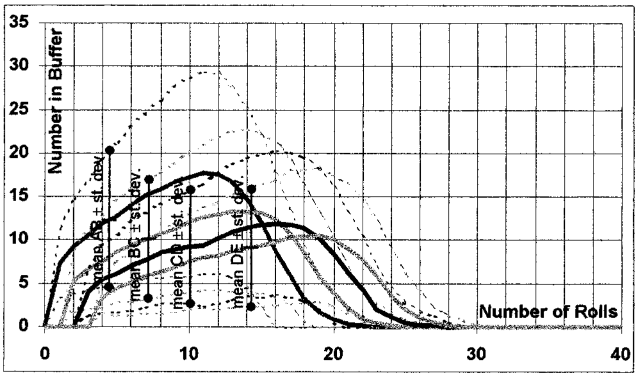

FIG. 11. Buffer Size from 1,000-Iteration Simulation Where All Players Have Fast Die (3-11)

(2) describes when each player can first start taking bolts from its buffer upstream, e.g., Sub A can always start at time 0, Sub B at time 1, etc. Column (3) lists when a player was able to complete its part of the project, e.g., when playing with an all-5 die, Sub A will always end by time 20. Column (4) gives the number of times a player had to roll the die to complete its part of the project. Column (5) describes the computed average number shown on the die at each roll, so it can be compared against the theoretical average of the die used. Finally, column (6) shows the average number of bolts that were actually passed in the game.

Additional system characteristics include the following. The average number of bolts passed is always less than or equal to the average actual roll. The slope also decreases from one model to the next (compare Figs. 2–4) when variability increases. Lower slopes mean lower production rates and thus wasted production capacity. With increased variability, intermediate buffers (work in progress) also grow larger. This means the crew is wasting time because its maximum production capacity cannot be achieved. Playing with dice with increasing variability increases the chance of finishing early, but also finishing late!

The next set of figures illustrates averages calculated after the games have been played 1,000 times (it takes the computer only a few minutes to do this!). Figs. 6–8 plot the number of rolls relative to cumulative production plus-or-minus one standard deviation, whereas Figs. 9–11 plot the number of rolls relative to the buffer size.

RELATED WORK AND DISCUSSION

The need to manage interdependence and uncertainty in construction has been recognized for a long time [e.g., Crichton (1966)]. Nevertheless, only deterministic modeling tools such as CPM appear to have gained acceptance in the industry. By contrast, probabilistic activity-based models [such as the program evaluation and review technique (PERT), which like CPM assumes sequential finality and no correlation between activities) or probabilistic process-based models [e.g., Halpin and Woodhead (1976)] remained largely academic. Recognizing the ubiquity of interdependence and uncertainty, it is clear that better tools must be developed for construction practitioners to manage work flow and production.

Computer games to help explain construction concepts were developed back in the late 1960s [e.g., Au and Parti (1969), Au et al. (1969)]. Existing games akin to the one presented here pertain to linear construction work, where construction progress can be represented by means of a line-of-balance or velocity chart. For instance, Harris and Evans (1977) describe a game for players to manage road construction. Their parade includes a fixed-order progression of seven processes. The player's challenge is to stepwise control production rates and buffer sizes by deciding on the size of labor crews, rates of supply of materials, numbers of machines, and hours to be worked, while random variations affect the outcome of each step.

Worthy of mention is that Harris and Evans dictate that a minimum buffer of 1 km of roadway be maintained between processes to move resources, store equipment, and handle materials. When players attempt production within the minimum buffer, operations are said to interfere and resources are wasted (Howell et al. 1993). Harris and Evans also observe that ''the effect of variability in early processes is diminished successively as each process is performed, due to the imposition of the minimum buffer'' [Harris and Evans (1977), p. 414]. Indeed, construction field practitioners use buffers to shield work from upstream uncertainty (Howell and Ballard 1996; Tommelein 1998).

The cost of repetitive-type construction certainly depends on the way the project is executed; it is not solely a function of the measured quantity of work it contains [also noted by Harris and Evans (1977) p. 413]. This is no surprise. The major task of any contractor is to determine means and methods. Nonetheless, means and methods alone are not the only determinates of performance for production. As the Parade Game illustrates, coordination among trades is equally important. Accordingly, contractors price their bids more favorably when they know that a skillful manager will coordinate their work with others on site [e.g., Birrell (1978), (1981), (1985) and Tommelein and Ballard (1997)].

CREATING RELIABLE FLOW IN PRACTICE

Owners, architect/engineers, and construction managers all play a key role in causing or preventing disruptions to construction work. They should understand the concept of reliable flow and apply it when selecting or evaluating subcontractors. Moreover, the Parade Game also illustrates the need to combine production planning with project planning.

Successful project managers put considerable effort into creating reliable flow for succeeding trades, e.g., they take proactive steps to establish buffers to shield crews from work flow variability. Common causes of unreliable flow are change orders, late replies to requests for information, lack of materials, physical interference between materials, work-space congestion, etc. Instead of accepting that delays and disruptions will rear their ugly head, practitioners must anticipate work flow variations and temper if not eliminate them by means of careful planning and paying attention to detail. This requires a hands-on approach to production management. Ballard and Howell (1998) proposed that crew foremen follow the Last Planner methodology to shield their workers from uncertainty and enable them to inject reliability into their work plans. Other proactive methods include setting flow rates and then requiring contractors to size their crews to meet these rates, while ensuring that work space will be available when needed. Space management techniques include defining zones and actively coordinating work areas, storage spaces, and traffic paths. These techniques seem basic, yet they are often overlooked and trades are left to work in random patterns or ''work out a sequence'' on their own.

The manufacturing industry has also been struggling with establishing reliable flow and reducing work in progress while increasing throughput. The theory of lean production provided them with new ways to think about these problems and achieve dramatic process improvements. In a similar vein, the writers are developing a theory for lean construction [e.g., Koskela (1992), Alarcon (1997), and Ballard et al. (1998)]. This paper is part of this development effort in that it sheds light on the impact of variability on tightly coupled construction processes.

COMPUTER IMPLEMENTATION

Hyun Jeong Choo implemented a stand-alone Parade Game program, that readers can download from http://www.ce.berkeley.edu/~tommelein/lean (Choo and Tommelein 1999). The figures in this paper were based on data generated with a discrete-event simulation model that uses STROBOSCOPE (Martinez 1996). The same system behavior can, of course, be shown manually or using any other simulation engine, but STROBOSCOPE was chosen for its ability to record intermediate data, such as buffer sizes and rolls. Readers interested in obtaining the STROBOSCOPE input file for the Parade Game may visit the aforementioned web site. Those wishing to download STROBOSCOPE should visit http://www/strobos.ce.vt.edu/.

CONCLUSIONS

A simple game was presented to illustrate the impact variability has on work flow in a single-line production system, which is so characteristic of the parade of trades formed by subcontractors on many a project. The game does not require many resources to be played, e.g., a cut-up 2-by-2 piece of lumber makes for easy-to-see, large dice, and blank dice are also available commercially. Nevertheless, it does allow the players to develop a better, intuitive understanding of several fundamental production concepts, including variability and throughput. It was shown that unreliable work flow results in two kinds of waste: (1) Production stations cannot realize their full production capacity because they starve for resources; and (2) intermediate buffers are larger when high variability prevails. Managers interested in schedule compression will benefit from understanding work flow variability's impact on succeeding trade performance.

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