Automation and Robotics in Construction XI
D.A. Chamberlain (Editor)
1994 Elsevier Science B.V.

Computer simultion of concrete slab-on-grade construction

Osama Moselhi and Stanley Hason

Centre for Building Studies, Concordia University, 1455, de Maisonneuve Blvd. West, Montreal, Quebec, H3G 1M8, CANADA.

Abstract

This paper presents a decision support system for contractors specialized in concrete floor finishing, making optimal use of available technology in automation. The paper presents a computer simulation model for concrete slab-on-grade construction considering different levels of automation that integrate conventional manual, semi-automated, and robotic work processes. The data used in the simulation was obtained through a survey of Montreal area ready-mix concrete plants, structured interviews with contractors, and site visits. The computer model is developed to assist those speciality contractors in selecting the most effective level of automation for their respective work environments and in visualizing the impact of the production rate of each individual task on the completion time of the entire process.

1. INTRODUCTION

In virtually all industrial applications, concrete slab-on-grade represents the finished surface upon which daily work is carried out, and therefore has both functional and aesthetic value. Its serviceability is entirely dependent on achieving a hard, flat and levelled surface which is free of cracks. Yet, concrete slabs-on-grade have for many years been the source of owners' and plant managers' displeasure. Studies since the early 1960's indicated that slabs-on-grade represent a significant proportion of building defect problems in both the United States and Canada (Moselhi et al 1993). Additionally, in recent years, the changing needs of owners have increased the pressure on contractors for more effective and rapid construction, and, paradoxically, for unprecedented accuracy in floor slab construction. Concurrently warehouses and distribution facilities have themselves been revolutionized by developments in automation, such as Automated Guided Vehicles or air pallet material handling systems, and computer controlled Very-Narrow-Aisle high-bay storage and retrieval systems, which require extremely precise floor surface tolerances. Faced with a rigorous, labour intensive construction process exhibiting common quality problems and subject to increasingly demanding owner requirements, slab on grade contractors need the productivity and quality improvements afforded by automation.

This paper presents a computer simulation model for concrete slab-on-grade construction considering different levels of automation that integrate conventional manual, semi-automated, and robotic work processes. The computer model is developed to assist speciality contractor in this field in selecting the most effective level of automation for their respective work environment, and in visualizing the impact of such selection on the production rates of the individual tasks and the completion time of the entire process. The data used in the simulation was obtained through a survey of Montreal area ready-mix concrete plants, structured interviews with 5 local concrete contractors, and observations of placing and finishing crews on 15 construction sites. The participants ranged from a small company with four employees, an annual operating revenue of $0.25 million, and an annual production volume of 400,000 sq. ft to perhaps the largest concrete finishing in Quebec, with 25 employees, an annual revenue of $1.5 million, and an annual production volume of 4 million sq. ft.. The sites were chosen to reflect different uses and were of different shape and size. The simulations are performed using MicroCYCLONE (Halpin 1990) for the placing and finishing of a unit slab as described in the following sections. Speciality contractors can interactively utilize the developed model in simulating the construction process, and accordingly select the most appropriate level of automation.

2. PRODUCTIVITY ANALYSIS

A comprehensive productivity analysis of the concrete slab-on-grade construction has been described in an earlier study (Moselhi et al 1992) and will be briefly summarized here for continuity. The data collected from the 15 sites was used to model concrete placing productivity, defined as the number of man-hours required to place one cubic meter of concrete, for a 150mm (6 in.) thick slab. It has been found (Moselhi et al 1992) that for both conventional manual and semi-automated placing, the best-fit functions to be:

$$\log(Y) = \log 1.66 - 0.18\log(X) \qquad (1)$$

with a coefficient of correlation of r^2=0.78, for manual placing, and,

$$\log(Y) = \log 3.7 - 0.37\log(X),1 \qquad (2)$$

with a coefficient of correlation of r^2=0.88, for semi-automated placing,

where: Y = placing crew productivity (m-hrs/m^3)
X = daily pour size (m^2)

In general, concrete placing productivity was found to vary with the size of the daily pour: for small pours (_ 930 m^2; 10,000 ft^2) the productivity is lower since relatively large crews must be assembled; as the daily pour size increases, so does productivity benefiting from the optimum utilization of the crew and the learning curve effect. Compared to conventional manual placing, semi-automated placing was found to increase productivity by reducing the manpower required to pour the floor. Thus, although the duration of semi-automated placing was not found to vary significantly from that of manual placing, the reduction in required manpower results in improved productivity.

Unlike concrete placing productivity, the productivity of concrete finishing varies greatly depending on the experience of the operator, the amount of water in the concrete, and the weather. If the concrete is free of excess water, and the weather is very warm, it was found that finishing may start as soon as half an hour after the concrete is placed and screeded; in this case, the rapid hardening will cause many difficulties to the contractor who must work fast. If the concrete contains excess water, and the weather is cold and damp, finishing may start as much as six hours after placing and screeding, and the whole floor may take more than 50% longer to finish. Accordingly, contractors' estimates of finishers' productivity varied enormously, ranging from 93 to 370 m^2/hr (1,000 to 4,000 ft^2/hr). Site measurements of finishing productivity with a 1.2m (46 in.) power trowel, under near ideal ambient conditions indicate productivity in the range of 185 to 250 m^2/hr (2,000 to 2,700 ft^2/hr). This is slightly lower than the productivity suggested by Peurifoy and Oberlender (1989), i.e., 280 to 370 m^2/hr (3,000 to 4,000 ft^2/hr) with a 1.2 m (46 in.) machine. Comparatively, the reported productivity of floor finishing robots (Moselhi et al 1992) varies from 300 to 800 m^2/hr (3,228 to 8,608 ft^2/hr).

3. PROCESS SIMULATION

In order to provide a better understanding of the results obtained, a model of concrete slab-on-grade construction process is developed and daily production cycles are simulated for various levels of automation. MicrOCYCLONE (Halpin 1976) was used to simulate the process. The model is shown in Figure 1. The squares and circles, are used in the model to describe, respectively, active and passive work states. These together with directed arrows (arcs) for resource flow direction, help provide a quick visual grasp of the structure of a construction operation. For a detailed definition of the language, the reader is referred to the MicroCYCLONE system and user's manuals.

3.1. Simulation Parameters and Assumptions

A model of the slab-on-grade construction process is developed and simulations are performed for the following four levels of automation:

- conventional manual construction: manual placing and manual finishing (MP/MF)
- automation of placing alone: semi-automated placing and manual finishing (SAP/MF)
- automation of finishing alone: manual placing and robotic finishing (MP/RF)
- automation of the entire process: semi automated placing and robotic finishing (SAP/RF).

The simulations are performed for the placing and finishing of a unit slab. The slab is 30x62 m^2 (100x200 ft^2) in area, 150 mm (6 in.) thick, nominally reinforced, made of 24 Mpa, 125 mm slump concrete. The following assumptions were made:

1. Work task breakdowns and crew sizes for each level of automation are given in Table 1, and are based on the construction practices in the Montreal area described in an earlier study (Moselhi et al 1992). It must be noted in Table 1 that robotic finishing, in accordance with the

contractors' comments, is assumed to be performed only for troweling: floating operations are performed with the mechanical power trowel.

2. Concrete is discharged from each truck in 3 batches of $3.4m^3$ each (this volume represents the amount of concrete required for one cycle of the semi-automated placing machine). Thus a total of 83 cycles are required to pour the unit slab.

3. For the conventional manual process and the automation of finishing alone, concrete placing productivity (Pp) for the unit slab is obtained directly from Equation 1. Thus,

$$Pp = 0.42 \text{ m-hrs/m}^3$$

Table 1
Work Task Breakdown and Crew Sizes for Various Levels of Automation

Work Task/Activity	Crew Size			
	MP/MF[2]	SAP/MF[2]	MP/RF[2]	SAP/RF[2]
Position Truck[1]	-	-	-	-
Spread Concrete (total)	5	5	5	6
discharge concrete	1	1	1	1
spread concrete with shovel	3	3	3	4
lift wire mesh	1	1	1	1
Screed Concrete (total	7	3	7	3
place concrete with rake				
set wet screed guide	3	-	3	-
screed and bullfloat	1	-	1	-
drive laser screed	3	-	3	-
screed slab edges	-	1	-	1
	-	2	-	2
Wait Concrete set	-	-	-	-
1st Float	1	1	1	2
Wait	-	-	-	-
2nd Float	1	1	1	2
Wait	-	-	-	-
3rd Float	1	1	1	2
Wait	-	-	-	-
1st Trowel	1	1		
Wait	-	-		
2nd Trowel	1	1		
Wait	-	-	1	1
3rd Trowel	1	1		

[1]Activity not performed by concrete contractor's crew
[2]As described in the text

For the automation of placing alone, placing productivity is obtained from Equation 2. Thus,

$$Pp = 0.25 \text{ m-hrs/m}^3 \tag{3}$$

In the case of the automation of the entire operation, where increased productivity can be sustained throughout the operation, placing productivity is conservatively assumed to be double that achievable by the automation of placing alone. Thus,

$$Pp = 0.125 \text{ m-hrs/m}^3 \qquad (4)$$

Since ideal ambient conditions are assumed for the entire duration of the operation, finishing productivity is assumed to be equivalent to that of placing for all cases.

4. Sufficient concrete is available to ensure that the system is not constrained due to lack of material. This implies that the supply of concrete is constant during the entire length of the pour and is based on the productive capacity of the crew. This assumption reflects actual working conditions encountered on site.

5. The relationships between concrete placing and the first floating pass, and between successive floating and troweling passes, are start-to-start with a lag to account for setting time of concrete. Thus, the start of the first floating pass is dependent on the start of concrete placing plus a four hour setting period. Similarly, the start of each finishing operation after the first pass is dependent on the start of the previous finishing operation plus a one hour setting period.

6. Work tasks have fixed durations. This is a reasonable assumption for this process because although work tasks may be subject to small variations about a specific mean, the

Table 2
Work Task Duration for Various Levels of Automation

Work Task/Activity	Duration (min)			
	MP/MF[1]	SAP/MF[1]	MP/RF[1]	SAP/RF[1]
Position Truck	1	1	1	1
Spread Concrete	3	2.7	3	1
Screed Concrete	4	3.7	4	2
Wait Concrete set	240	240	240	240
1st Float	7	6.4	7	3
Wait	60	60	60	60
2nd Float	7	6.4	7	3
Wait	60	60	60	60
3rd Float	7	6.4	7	3
Wait	60	60	60	60
1st Trowel	7	6.4	7	3
Wait	60	6	0	60
2nd Trowel	7	6.4	7	3
Wait	60	60	60	60
3rd Trowel	7	6.4	7	3

impact of these variations on productivity can be considered small or insignificant. Durations for the specified work tasks are presented in Table 2.

7. MicroCYCLONE requires that the total duration of the run be specified, although the simulation will stop at whichever occurs first, the total duration of the run or the total number of

cycles. Since the controlling parameter in this simulation is processing the total number of cycles, a sufficiently large total duration of 1440 minutes (1 day) is specified.

3.2 Process Model

The model network diagram is presented in Figure 1. The resources required to run the simulation are listed in Table 3. The network can be broken down into three groups of activities.

Table 3
Resources Required for Simulation

Node	Resources			
	MP/MF[1]	SAP/MF[1]	MP/RF[1]	SAP/RF[1]
QUE 1	1 truck	1 truck	1 truck	1 truck
QUE 6	1 permit to reposition truck	1 permit to reposition truck	1 permit to reposition truck	1 permit to reposition truck
QUE 8	1 12-man placing crew	1 8-man placing crew	1 12-man placing crew	1 9-man placing crew
QUE 27	3 concrete finishers	3 concrete finishers	3 concrete finishers	6 concrete finishers
QUE 28	3 concrete finishers	3 concrete finishers	3 finishing robot + 1 supervisor	3 finishing robot + 1 supervisor
QUE 35	Counter initialized @ 1	Counter initialized @ 1	Counter initialized @ 1	Counter initialized @ 1

[1] As described in the text

Nodes 1 to 8 represent the concrete placing cycle. At the beginning of this cycle, a concrete truck is generated at QUE node 1 and broken down into 3 batches of 3.4 m^3 each. The truck is positioned (COMBI node 2), and, if the concrete placing crew is available (QUE node 8), a batch of concrete is discharged (COMBI node 4). At this point commands are released which permit both the truck to be repositioned (QUE node 6) and the placing crew to spreak, screed, and bullfloat the concrete (NORMAL node 7). When 5 batches are discharged, a command is given (FUNCTION node 5) to generate a new truck at QUE node 1.

Nodes 9 to 28 represent the concrete finishing cycle, composed of three floating passes (COMBI nodes 16, 18, 20) and three troweling passes (COMBI nodes 22, 24, 26). These are, in essence, sequential but staggered activities with the first pass starting 4 hours after the first batch of concrete is placed (NORMAL node) and the subsequent passes beginning at 1 hour intervals (NORMAL nodes 10, 11, 12, 13, 14).

Because of the 4 hour time lag between the placing and finishing cycles, and because MicroCYCLONE allows the use of only one counter per model, a mechanism is required to ensure that the proper number of flow units are both initialized and processed. Nodes 29 to 35 represent this mechanism, monitoring and controlling the total quantity of concrete in both placing and finishing cycles at all times.

3.3 Daily Production Cycles

The results of the simulation of the placing and finishing of a unit slab are shown in Figure 2, in which the vertical axis represents the quantity of concrete being placed (in m^2), and the horizontal represents time (hrs). Figure 2 shows the daily production cycle for conventional manual construction. The production rate of the placing crew is represented by the first line on the left. The six lines on the right of the placing line represents each of the three floating and three troweling passes. The total duration is 1129.5 minutes (18 hrs 50 min). Figure 2 also represents the daily production cycle for the automation of finishing alone because the productivity of the robot is limited by the achievable productivity of the human operators. Similar daily production cycles were generated for the other cases, representing different levels of automation.

4. ECONOMIC EVALUATION

Based on the simulations performed and the resources utilized, the cost associated with each alternative can easily be calculated. Accordingly, the economic feasibility of the automation of concrete placing and finishing, implemented either separately or jointly, can be determined by comparison with the conventional manual process (e.g. as described in (Moselhi et al 1992)).

CONCLUSIONS

The simulation clearly demonstrates that slab on-grade construction is a sequential process necessitating a constant production rate during delivery, placing, and finishing. There are no interacting cycles competing for resources: each batch of concrete as discharged from the truck is processed by each work task without delay.

The results of a change in the productivity of any one operation alone is immediately apparent, as the slope of that operation would either increase or decrease rendering it 'out of balance' with previous or successive operations. For example, if the arrival or repositioning time of a truck (nodes 1 to 5) exceeds the time required to place a batch of concrete (nodes 4-7-8), the placing crew's productivity would decrease, thus reducing the slope of the placing line. This would require a similar reduction in the productivity of the other operations until the delivery rate is brought back to normal. The ability to visualize the impact of these charges on the completion time of the entire process, provides contractors with a useful decision support for selecting the level of automation that satisfies their respective project constraints.

REFERENCES

1. Moselhi, O., Fazio, P. and Hason, S., (1992). "Automation of Concrete Slab-on-grade Construction", ASCE Journal of Construction Engineering and Management, Vol. 118, No.4.
2. Halpin, D.W., (1990). MicroCYCLONE user's manual. Division of Construction Engineering and Management, Purdue University, West Lafayette, IN.
3. Peurifoy, R.L. and Oberlender, G.D., (1989). Estimating Construction Costs, 4th edition, McGraw-Hill Book Co., New York, N.Y.

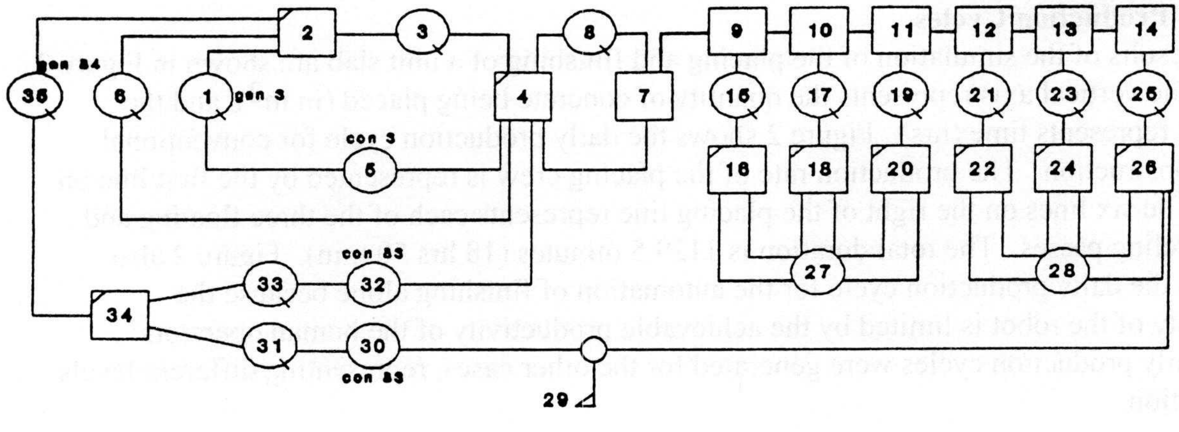

Figure 1: Process Model

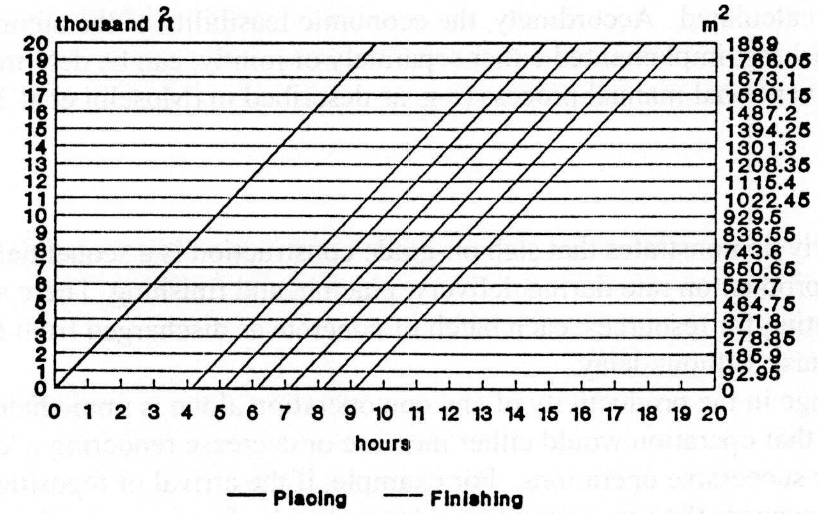

Figure 2: Production Rates