Automation of Concrete Slab-on-Grade Construction

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Abstract: This paper addresses the effective use of various levels of automation in concrete slab-on-grade construction, considering conventional manual construction, semiautomated placing using a laser-guided screeding machine and automated finishing using a robotic floor finisher. For both manual construction and semiautomated placing, information is obtained through structured interviews of concrete contractors and site observations. Information on robotic finishing is obtained from robot developers. When compared to the conventional manual construction of a typical 1,859-m^2, 150-mm-thick slab, accomplished in 10 hours with a 12-man placing crew and a six-man finishing crew, automation of finishing alone is found to offer benefits through a 30% reduction in the size of the finishing crew, whereas automation of placing alone offers benefits through a 33% reduction in the placing crew size and a 20% activity-duration reduction. Automation of both placing and finishing allows a 33% placing-crew-reduction, 25% finishing-crew increase, and a 60% activity-duration reduction. These benefits are considerably increased when higher quality is explicitly specified.

Introduction

Over the past decade, many industrialized countries have realized that the problems facing their respective construction industries, namely, declining productivity, increasing labor and safety costs, and changing workforce demographics, could be alleviated by using the same technologies that have benefited manufacturing industries in dealing with similar problems, i.e., automation and robotics. Although considerable research has focused on hardware and software developments for construction applications (Hasegawa 1991; Tucker 1991), relatively little attention has been paid to the planning and implementation concerns faced by the eventual end user of the technology, i.e., contractors. Faced with new working strategies, contractors will need to integrate manual, mechanized, partially automated, and fully automated work processes in such a way as to allow the benefits of each to be fully realized, but without requiring that dependent operations be of equal level of automation. This will require knowledge of traditional methods and an in-depth understanding of the automated process and its impact on the operation's constraints.

This paper presents an analysis of the practical implications of implementing construction automation by considering the automation of concrete slab-on-grade construction through semiautomated concrete placing and robotic floor finishing. An in-depth analysis of conventional manual concrete

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placing and finishing operations was performed. Information on current industry practices in the Montreal area was obtained through a survey of local concrete ready-mix concrete plants, structured interviews with five concrete contractors, and observations of placing and finishing crews. The quality controlling elements of current practices are identified and compared to those of the automated processes. Production rates are analyzed for different combinations of manual and automated work, and an economic analysis is performed to compare the cost of various levels of automation and to determine areas of economic advantage.

BACKGROUND

In virtually all industrial applications, the 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 therefore entirely dependent on achieving a hard, durable, flat, and leveled surface that is free of cracks. Yet, concrete slabs on grade have for many years been the source of owners' and plant managers' displeasure. In the early 1960s, slabs-on-grade represented a significant proportion of building defect problems in both the United States (Ytterberg 1961) and Canada (Dickens 1961). These were comparatively rarely due to settlement or other major structural causes, but were more commonly due to poor performance of the surface. Today, experience suggests that floor-surface quality varies tremendously, regardless of the construction method, and that floors still commonly experience problems, perhaps even more than 25 years ago (Ytterberg 1987; Garber 1988).

Additionally, in recent years, the changing needs of owners have increased the pressure on contractors for more cost-effective and rapid construction, and, paradoxically, for unprecedented accuracy in floor slab construction as 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, labor-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.

QUALITY: DEFINITION AND MAJOR CONTRIBUTING FACTORS

For the pupose of this analysis, slab on grade refers to a nonstructural, monolithic slab, continuously supported by a flat and uniform load-bearing subgrade, constructed in an enclosed but nonclimate-controlled space (i.e., subject to external temperature and humidity variations). The quality of a slab-on-grade is determined by its conformance with the following essential performance requirements: (1) Adequate load-bearing capacity; (2) minimal cracking and curling; (3) abrasion-resistant surface; and (4) flat and leveled surface. Whereas standard test procedures exist to evaluate the requirements related to the properties of the concrete mix, such as strength, slump, and shrinkage, there have been until recently few effective methods for specifying the essential performance requirements of concrete slabs: such is the case for thickness tolerances (Gustafero 1989; Snell and Rutledge 1989) and abrasion resistance ("Guide" 1977).

With respect to flatness and levelness, the traditional method, known as

TABLE 1. Flatness/Levelness Classifications ("Guide" 1989)

Classification (1)	F_f (2)	F_l (3)	Approximate gap under 3.05-m (10-ft) straightedge (4)
Minimum acceptable	13	10	—
Conventional bull-float	15	13	12.7 mm (1/2 in.)
Conventional straightedge	20	15	7.9 mm (5/16 in.)
Flat	30	20	4.8 mm (3/16 in.)
Very flat	50	30	3.2 mm (1/8 in.)
Superflat	100	—	—

the "3.2 mm in 3.05 m" rule (1/8 in. in 10 ft), which requires measuring the maximum gap under a 3.05-m- (10-ft-) long straightedge, is widely recognized as a poor method for specifying floor tolerances (Phelan 1988; Stephan 1989). A new method has recently been developed, called the F-number method, in which the floor-surface profile is determined by sampling, within 24 hours after placement, a number of normally distributed floor elevations ("Guide" 1989). Numerical values are then assigned to describe flatness, F_f, which is characterized by the maximum floor curvature over 610 mm (24 in.), and levelness, F_l, which is characterized by the floor slope over a distance of 3.05 m (10 ft). F_f/F_l classifications for different floor categories are given in Table 1.

Although dependent on proper design, slab quality is perhaps determined to a greater extent by proper workmanship and construction techniques. Slab-on-grade construction follows the basic fuctional steps of any concreting operation, namely, manufacture of the concrete mix, delivery to work site, transfer to the workplace, and placement and treatment, and should therefore adhere to standard practices for concrete handling, placing, finishing, and curing ("Guide" 1989). There are, however, a number of unique factors to be cosidered in achieving a quality slab: these are summarized in Table 2.

Levels of Automation

Semiautomated Concrete Placing

The automation of concrete placing through laser-guided screeding is an example of the growing use of laser technology in construction (Tatum and Funke 1988; De Boer 1991; Pruitt 1987). A number of approaches to laser-guided screeding have been developed, namely, truss-type rail-mounted (Nomura et al. 1989; Yoshitake et al. 1991), ski-mounted (Smith 1991), and retractable vehicle-mounted (Fling 1987). The latter approach offers significant advantages over the former in that it allows wide pour widths, therefore reducing the need for rails, forms, or other screed guides, and has been in use since 1986 (Kinney 1991).

The laser-guided screeding machine used in the present study (Fig. 1) is a four-wheel–drive vehicle supporting a 6-m- (20-ft-) long telescoping boom, at the end of which is attached a 3.7-mm- (12-ft-) wide carriage that can be raised or lowered by a pair of hydraulic masts. The carriage houses a 230-mm- (9-in.-) diameter auger that uniformly distributes the concrete, and a vibrating straightedge that strikes off the surface. A self-leveling rotating laser is set up outside the work area, defining a reference plane parallel to the design grade. Laser receptors are permanently mounted on the machine

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TABLE 2. Factors/Operations Having Greatest Impact on Slab Quality

Essential performance requirements (1)	Factor/ operation (2)	Impact (3)
Load bearing capacity	Grading and concrete placing	Apart from compaction of sugrade, load-bearing capacity is dependent on slab thickness (and strength), and is therefore dependent on precision of both grading and concrete-placing operations
Abrasion resistance	Timing of finishing operations	Any finishing operation performed while there is excess moisture or bleeding on surface will reduce compressive strength at surface, thereby reducing abrasion resistance ("Guide" 1988).
	Troweling	By increasing the compaction of fines at surface, amount and quality of troweling is operation with greatest effect on abrasion resistance (Ytterberg 1987)
Levelness	Setting side forms and screeding to their elevation	Accuracy of performing these operations has a greater effect on achievable levelness than any other operation ("Guide" 1989)
	Placement width	As distance widens between forms, it becomes harder to achieve flat and level crack-free surface; in general, building F_f45/F_l30 floor with forms greater than 20–50 feet apart is very difficult (Phelan 1988)
	Use of wet screed guides	Limits achievement of surface quality to F_f20/F_l20 ("Guide" 1989)
Flatness	Use of bull float	Limits achievement of flatness to F_f20 ("Guide" 1989).
	Application of shake-on hardeners	Limits achievement of flatness to F_f45 (Phelan 1988).
	Timing and number of re-straightedging operations	As more such operations are performed at proper time between successive troweling operations, floor will be flatter, eventually becoming superflat

at each end of the carriage on the hydraulic masts. The point at which the laser beam strikes the recptors on the hydraulic masts is transmitted to a microprocessor, which calculates the difference between the desired and actual carriage elevation. As the boom is retracted, the microprocessor commands the hydraulic control system to raise or lower the masts at a frequency of five times a second.

During a typical cycle, the operator drives the machine up to the section being poured, puts down the hydraulic stabilizer pads, and positions the boom. The concrete is poured directly from the truck onto the subgrade in 3.7×6 m^2 (12×20 sq ft) sections, and must be manually spread approximately 25 mm (1 in.) above the finished floor grade, as too much or too little concrete in front of the carriage can cause bumps or valleys that have to be corrected with another screeding pass. The machine automatically retracts the boom, maintaining the proper carriage elevation. Automatic control can always be overridden by the operator in order to avoid obstruc-

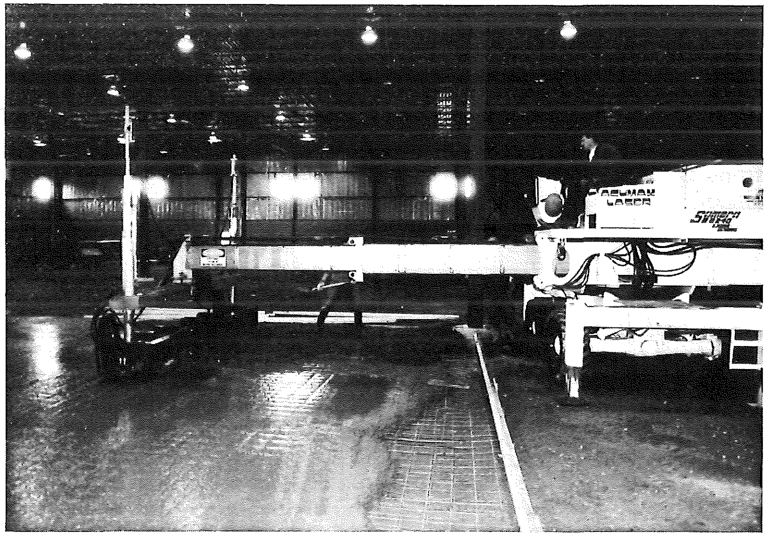

FIG. 1. Laser-Guided Screeding Machine

tions. The operator then drives the machine approximately 3.7 m (12 ft) across the pour width and repeats the process with about a one foot overlap with the previous pass. When working on the perimeter of the slab, the carriage is stopped approximately 1 m (3.28 ft) before the edge of the slab, which must then be poured and screeded by hand.

Robotic Floor Finishing

The automation of concrete floor finishing has been an area of great interest to leading Japanese contractors since their initial involvement with construction robotics. In 1984, a first attempt at developing a floor-finishing robot produced a device that imitated the action of a human operator finishing a slab. The device, which swept a trowel assembly back and forth much like a human finisher handles a power trowel, proved to be bulky, awkward, and difficult to program (Arai et al. 1988). More recent attempts have refined the design, producing a family of similar devices differing mostly in their degree of autonomy. Table 3 compares the characteristics of the four types of robotic floor finisher with those of a standard mechanical power trowel.

The robots typically consist of twin- or triple-trowel assemblies rotating around or behind a motorized unit traveling on rollers. As the unit advances, the trowels finish the surface, thereby erasing roller tracks. All four models presented in Table 3 can be teleoperated, and the last three models can also be programmed. Programming consists of entering the dimensions of the area to be finished, the overlap width, the initial travel direction, and setting the operating parameters such as travel speed, rpm, and blade angle. The on-board microcomputer then calculates the traveling pattern such that the entire area is covered by a series of transversal passes.

Since none of the models follow a fixed path or guidewire, a guidance system is necessary. For the first model in Table 3 this is accomplished by manual remote control. Reliable free-range guidance is presently achieved

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TABLE 3. Characteristics of Mechanical and Robotic Floor Finishers

Type		Characteristics										
Name (1)	Developer (2)	Weight (kg) (3)	Travel speed (m/min) (4)	Engine (rpm) (5)	Lapping width (m) (6)	Production Rate (m^2/hr) (7)	Control (8)	Trowel assembly (9)	Power (10)	Guidance/ navigation (11)	Obstacle avoidance (12)	Source (13)
Power trowel	Bartell, Honda, other equipment suppliers	70	—	50–135	0.91	230–280	Manual	1 × 4 blades	Gasoline engine	Manual	Manual	Peurifoy and Oberlender (1989)
Flatkn	Skimizu	300	0–10	70–100	2.30	400–800	Teleoperated	3 × 3 blades around unit	Self-contained gasoline engine and generator	Manual	Immediate stop on contact	Ueno et al. (1988)
Mark II	Kajima	185	0–13	—	1.20	450–700	Teleoperated preprogrammed	2 × 3 blades behind unit	Electrical through unbillical cable	(Relative) gyrocompass and encoder	Adaptive	Arai et al. (1988)
Surf Robo	Takenaka	185	0–12	0–35	2.14	300	Teleoperated preprogrammed	2 × 4 blades around unit	Electrical through unbillical cable	(Relative) gyrocompass and encoder	Touch sensor	Kikuchi et al. (1988)
—	Ohbayashi	—	0–10	—	1.56	500	Teleoperated preprogrammed	2 × 3 blades behind unit	Self-contained	(Relative) encoder and (absolute) laser	Touch sensor	Shiokawa et al. (1988)

by combining both relative position sensors, which provide continuous positional knowledge but are subject to cumulative errors, and absolute position sensors, which provide positional knowledge with respect to external reference points (Waldron and McGhee 1986). Of the programmable units in Table 3, only the last model combines both relative and absolute sensors: its developer indicates a positioning accuracy of 5 cm, and a heading accuracy of $\pm 0.5°$ for this unit (Nishide et al. 1988). The remaining programmable units use only relative position sensors but do not report any positional accuracy data.

Research Methodology

In an effort to compare different construction methods that integrate conventional manual, semiautomated, and robotic work processes, an in-depth analysis of current industry practices was performed. Information was collected through a survey of Montreal area ready-mix batch plants, structured interviews of local concrete contractors, and observations of their placing and finishing crews. Five Montreal firms specializing in concrete construction participated in the study. The participants ranged from a small company with four employees, an annual operating revenue of $250,000, and an annual volume of work of 37,180 m^2 (400,000 sq ft), to perhaps the largest concrete finishing contractor in Quebec, with 25 employees, an annual operating revenue of $1,500,000, and an annual volume of work of 371,802 m^2 (4,000,000 sq ft). Local construction practices were identified during interviews with each contractor by obtaining information about crew size and composition, and work scheduling and duration, for the placing and finishing of a standard concrete mix (f_c = 24-Mpa [125-mm] slump) under ideal ambient conditions (T = 21°C, RH = 50%). For each participant, three sites were visited, enabling firsthand observation of concreting crews and working practices.

Included among the study's participants is the first and only contractor to use a laser-guided screeding machine in the province of Quebec. Thus, actual operating and maintenance costs were obtained, and, through site observations, construction practices were analyzed. Information on concrete floor finishing robots, in the absence of actual data on their use, was obtained through published reports and discussions with Japanese contractors, and has been reported in a previous study (Moselhi and Hason 1989). In order to obtain the best possible understanding of the use of the robots, contractors were shown videotapes of floor-finishing robots, and were asked to provide their views on the perceived advantages and disadvantages of their use.

Productivity

Concrete Placing

The survey of local construction practices indicated very consistent work methods among small, medium, and large concrete contractors. Ready-mixed concrete is used in the construction of virtually all slabs-on-grade; none of the contractors indicated any experience with on-site batch plants. When no special requirements are specified, the conventional manual construction process is composed of direct from truck discharge, wide pour widths, usually two or three bays wide (18.3–30.5 m [60–100 ft]), wet screed guides (i.e., elevation guides struck off in the fresh concrete at the time of pouring), bull floating, finishing consisting of three float and three trowel passes, and curing by spray-applied compound.

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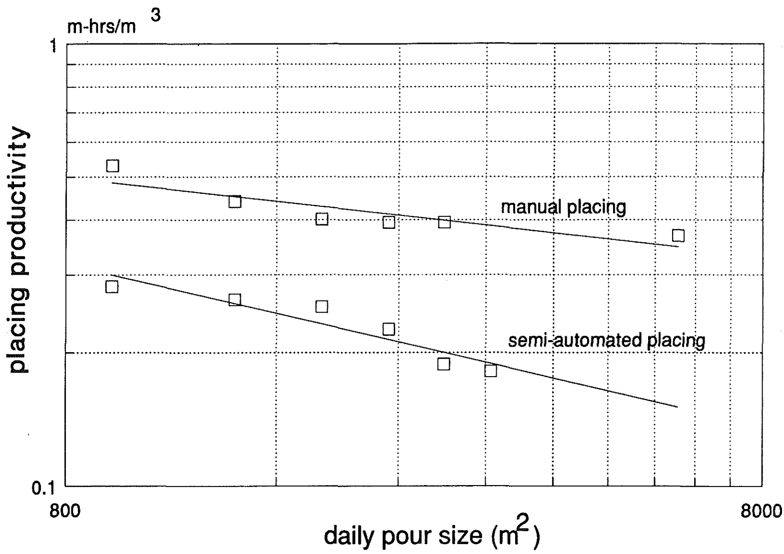

FIG. 2. Manual and Semiautomated Concrete Placing Productivity

Fig. 2 presents a comparative study of concrete placing productivity, defined as the number of man-hours required to place 1 m^3 of concrete, for a 150-mm- (6-in.-) thick slab, and for both manual and semiautomated placing. Although not meant to provide absolute results, it is clear from the consistency of the feedback received from the five highly specialized local contractors, that the data help establish clear trends. The best-fit functions for the data were found to be

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

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

$$\log(Y) = \log 3.7 - 0.37 \log(X) \quad (2)$$

with a coefficient of correlation of $r^2 = 0.88$, for semiautomated placing, where Y = placing crew productivity (manhours/m^3); and 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 ($\approx$930 m^2 [10,000 sq ft]) 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, semiautomated placing was found to increase productivity by reducing the manpower required to pour the floor. Thus, even though the duration of semiautomated placing was not found to vary significantly from that of manual placing, the reduction in required manpower results in improved productivity.

Floor Finishing

The productivity of concrete finishing varies greatly depending on the experience of the operator, the amount of water in the concrete, and the

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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 6 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 sq ft/hr). Site measurements of finishing productivity with a 1.2-m (46-in.) power trowel, under near ideal ambient conditions, indicate productivity in the range of 185–250 m^2/hr (2,000–2,700 sq ft/hr). This is slightly lower than the productivity suggested by Peurifoy and Oberlender (1989), i.e., 280–370 m^2/hr (3,000–4,000 sq ft/hr) with a 1.2-m (46-in.) machine. Comparatively, the reported productivity of floor finishing robots (Table 3) varies from 300 to 800 m^2/hr (3,228 to 8,608 sq ft/hr).

Placing and Finishing

The successful construction of a concrete slab-on-grade depends on achieving the target production rate during every step of the operation: thus the concrete delivery rate, the placing crew's production rate, and the finishing crew's production rate must be compatible. It is particularly important for the placing and finishing crews to achieve the same rate, for if the finishing crew's production rate were less than the placing crew's, the concrete would harden before it could be finished in time, and if the finishing crew's production rate were greater than the placing crew's, the finishing crew would find itself finishing concrete before it had time to set. Therefore, any equipment that significantly increases the production rate of either delivery, placing, or finishing cannot be used to its full potential unless a similar production rate increase is obtained in the other operation.

Thus, although local ready-mix batch plants surveyed indicated an average production capacity of 100–150 m^3/hr (130 to 196 cu yd/hr) and a capacity to supply concrete at up to 75 m^3/hr (98 cu yd/hr) without difficulty, concrete contractors indicated, however, that the fastest rate at which they will pour a conventional slab-on-grade is approximately 45–50 m^3/hr (58.8–65 cu yd/hr). This limitation is solely due to the fact that greater production rates require finishing manpower in excess of that which is available to most firms. In fact, overcoming shortages of concrete finishers was found to be the prime motivator for automation by local contractors.

Subject to the same manpower constraints, the greatest production rate for which semiautomated placing is planned is the same as that of manual placing. Thus, although a number of British contractors have suggested a production rate of 80–100 m^3/hr (105–131 cu yd/hr) with the laser-guided screeding machine (Barfoot 1988; "Fast track" 1989), its use by the local contractor is limited to a production rate equivalent to that of the manual placing operation by the inability to achieve the required finishing rate rather than by the inability to achieve the concrete supply rate. Robotic finishers could help contractors benefit from the full potential of semiautomated placing. For example, assuming a 6-in. floor thickness, the upper bound of robot production rates (Table 3) is beyond the range of semiautomated placement rates.

Quality

While recognizing that achievable surface quality can vary considerably for a given construction method, the information collected in this survey

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suggests that the steps taken by Montreal area contractors in the construction of a conventional concrete slab on grade limits the achievable surface quality to approximately F_f20/F_l20. The principal factors that limit quality are the use of wide pour widths, the use of the bull float, and the difficulty in achieving correct elevations with wet screed guides.

Eliminating the need for wet screed guides that limit achievable levelness to F_l20, is one of the greatest benefits of semiautomated placing. Analyses of floors produced by the laser-guided screeding machine indicate a capacity to achieve a surface levelness of approximately F_l45, with placement widths of 30 m (100 ft) or more ("Laser-guided" 1989; Fricks 1991). Such a floor, if done conventionally, would require pouring the concrete in 6-m (20-ft) strips and several corrective straightedgings. Another significant improvement is achieved by eliminating the use of the bullfloat, which limits achievable flatness to F_f20, through the use of the straightedge, which is considered by the American Concrete Institute (ACI) as the only tool capable of flattening a concrete surface (see Table 2).

The machine's ability to handle stiff concrete, with slumps as low as 75 mm (3 in.), leads to less bleeding, higher strength, higher density, and generally higher-quality floors. Less bleeding and lower slump also speed the setting process, thereby reducing the operation's duration. When used in conjunction with semiautomated subgrade compaction control systems and laser-guided grading systems currently available on the market (Ferris 1985; Tatum and Funke 1988), semiautomated placing leads to improved strength through more uniform slab thickness and, in addition, may allow material savings.

The surface quality obtained with robotic finishers is quoted by their manufacturers as being equal to or better than that obtained by a human operator with a machine. There are, however, special quality concerns that must be considered in planning their use. For example, the execution of the finisher's work requires, in general, considerable judgment, as it is crucial to physically feel and see the effects of the trowel on the concrete surface in order to judge where and how fast to travel, and to maintain control over the quality of work. The first float pass in particular is probably the most critical step because, at this point, the surface is still plastic enough to allow minor defects to be corrected. These defects may require the operator to use a different finishing pattern: low spots, for instance, are filled by going around them in a clockwise direction, then continuing with the regular pattern. Also during the first pass, the operator recognizes the areas that set faster and must float them first: these typically include areas adjacent to walls, columns, doorways, or specific areas that may be exposed to the sun or wind. Consequently, none of the contractors interviewed were confident about removing the operator from the concrete surface during floating operations; all, however, indicated that they would not hesitate using the robot during troweling operations.

Economic Analysis

The economic feasibility of different levels of slab-on-grade construction automation is determined by comparison with that of the conventional manual process (manual placing [MP]/manual finishing [MF]) as defined in the survey: the levels considered are automation of placing alone (semiautomated placing [SAP] and manual finishing [MF]), automation of finishing alone (manual placing [MP] and robotic finishing [RF]), and automation of the entire process (semiautomated placing [SAP] and robotic finishing [RF]).

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The comparison is based on a net present value (NPV) analysis for which the following assumptions are made.

1. Concrete contractors' business environment is characterized by strong price competition, where contracts are awarded to the lowest bidder. Whether hired by the general contractor or directly by the owner, the employer knows the unit market price for a specified quality and is unwilling to pay more than what he considers to be the going rate. Hansen and Tatum (1989) have described this environment as *reciprocal competition*, in which companies compete from very similar positions relying on operating differences to obtain contracts. This suggests that increased operating costs that result from capital equipment purchases cannot be passed on to the consumer unless all firms experience the same conditions. Thus, although offering a higher-quality product at a higher operating cost, the contractor using the laser-guided screeding machine cannot charge more than the going market rate for a conventional floor. When bidding, however, on a floor that explicitly specifies high-surface quality, he would benefit from a distinct advantage over contractors who base their bids on conventional manual construction.
2. The value of each alternative is determined for a constant annual volume of work (square meters) over a four-year time horizon. Although in practice different types and sized of slabs would be poured in one year, for the purpose of this analysis, the contractor's annual work volume is based on the construction of a *unit slab*, representing a size into which a larger slab can be conveniently subdivided. Although dependent on individual schedule and resource constraints, most contractors indicated that 1,673–1,952 m^2 (18,000–21,000 sq ft) in area can be accepted as a guide for an average daily pour size under normal circumstances. The unit slab is therefore defined as made of 24-Mpa (125-mm) slump concrete, nominally reinforced, having an area of 30×62 m^2 (100×200 sq ft) and a thickness of 150 mm (6 in.).
3. The concrete placing productivity for which the unit slab is modeled is obtained from (1) in the case of MP/MF and MP/RF, and (2) in the case of SAP/MF. 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. In the case of SAP/RF, where increased productivity can be sustained throughout the operation, the production rate is conservatively assumed to be 70 m^3/hr (91 cu yd/hr), or approximately 50% greater than the maximum production rate achievable by the conventional manual process. It is also assumed, as per the indication of the survey participants, that all floating operations are performed manually, whereas troweling operations are robotized.

Base Case Economic Parameters

The composition and cost of crews for the different alternatives are given in Table 4: the hourly wage rates represent the gross salary plus all benefits and contributions for cement floor finishers and laborers in the province of Quebec in 1990 ("Hourly labour" 1990). Capital costs as well as operation, transportation, and maintenance costs are given in Table 5. In general, all of the parameters except those related to the robot finisher have been determined based on the information obtained from the survey. The capital

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TABLE 4. Composition and Cost of Crews for Various Levels of Automation

Task (1)	Manual Placing/ Manual Finishing (MP/MF)		Manual Placing/ Robot Finishing (MP/RF)		Semiautomated Placing/Manual Finishing (SAP/MF)		Semiautomated Placing/Robot Finishing (SAP/RF)	
	Men (2)	Cost ($/hr) (3)	Men (4)	Cost ($/hr) (5)	Men (6)	Cost ($/hr) (7)	Men (8)	Cost ($/hr) (9)
Control truck chute	1	19.70	1	19.70	1	19.70	1	19.70
Spread concrete with shovel	3	19.70	3	19.70	3	19.70	3	19.70
Place concrete with rake	3	19.70	3	19.70	—	—	—	—
Lift wire mesh	1	19.70	1	19.70	1	19.70	—	19.70
Screed concrete	3	27.30	3	27.30	—	—	—	—
Read transit	1	19.70	1	19.70	—	—	—	—
Driver laser screed	—	—	—	—	1	27.30	1	27.30
Screed edges	—	—	—	—	2	27.30	2	27.30
Total placing	12	259.20	12	259.20	8	180.4	8	180.4
Float and trowel	6	27.30	4.25	27.30	6	27.30	7.5	27.30
Total finishing	—	163.80	—	116.03	—	163.80	—	204.75

TABLE 5. Summary Cost Table

Equipment (1)	Manual Placing/ Manual Finishing (MP/MF)		Manual Placing/ Robot Finishing (MP/RF)		Semiautomated Placing/Manual Finishing (SAP/MF)		Semiautomated Placing/Robot Finishing (SAP/RF)	
	No. (2)	Cost/unit ($) (3)	No. (4)	Cost/unit ($) (5)	No. (6)	Cost/unit ($) (7)	No. (8)	Cost/unit ($) (9)
Power floater	6	2,500	3	2,500	6	2,500	6	2,500
Truck	1	25,000		25,000	1	25,000	1	25,000
Robot finisher	0		3	50,000	0		3	50,000
Truck	0		0		0		0	
Screeding machine	0		0		1	227,500	1	227,500
Truck	0		0		1	50,000	1	50,000
Total capital cost	—	40,000	—	182,500	—	317,500	—	467,500
Operating and transportation cost per unit slab	—	150	—	250	—	350	—	450
Maintenance cost per 2,500,000 sq ft	—	3,000	—	16,500	—	43,000	—	58,000

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cost for the robotic finisher represents an estimated average value based on discussions with Japanese developers, for which variations can be accounted for in a sensitivity analysis. Robot operating costs (fuel or electric power) are estimated based on similar characteristics of power trowels. Robot maintenance costs are estimated at 5% of capital costs based on information obtained from Japanese developers. An escalation factor of 4% is used to adjust all costs except capital costs.

Revenues are based on the going market rate for a conventional slab on grade in Montreal, i.e., approximately $5.38/m^2 (50 sq ft). For Canadian income tax purposes, the method of depreciation used is the declining balance with one-half of the net capital cost of the asset added to the asset pool in the first year, and the remainder added in the following year: the mandated depreciation rate is 30% (Davis and Pinches 1988). The combined federal and provincial tax rate is 30% and a minimum attractive rate of return of 10% is assumed.

Analysis

Fig. 3 compares the unit cost of the different levels of automation with that of the conventional manual process. The figure shows that automation of both placing and finishing requires a minimum annual volume of work of 144,321 m^2 (1,600,000 sq ft) to be more economical than the conventional manual process, whereas the automation of placing alone requires 191,030 m^2 (2,100,000 sq ft), and the automation of finishing alone requires 330,911 m^2 (3,600,000 sq ft). This latter alternative provides very little difference in unit cost in its feasible range when compared to the conventional manual process, whereas automation of placing alone and of both placing and finishing offer significant unit-cost reductions.

In order to determine the effect of variations in base case parameters on the feasibility of different levels of automation, a sensitivity analysis was performed. Fig. 4 represents the effect of variations in the labor rate, normalized and expressed as percentage variation from the base case, on the annual volume of work that is required for each level of automation to be more economical than the conventional manual process. For example, a 10% increase in labor rates from the base case, represented by the normalized value of 1.1, reduces the annual volume of work required for each alternative to be more economical than MP/MF by 12.1% in the case of automated placing and finishing, 13.4% for automated placing alone, and 14.8% for automated finishing alone.

Similarly, Fig. 5 shows the effects of capital cost variations, normalized and expressed as percentage variation from the base case, on the annual volume of work that is required for each alternative to be more economical than MP/MF. Thus, a 10% increase in the cost of the robot finisher alone would increase the annual work volume required for its use to be more economical than MP/MF by 10.5%. A 10% increase in the cost of the semiautomated screeding machine would increase the required annual work volume by 8.2%, and a 10% increase in both the robot finisher and the semiautomated screeding machine would increase the required annual work volume by 8.8%.

In general, allowing for a possible 10% variation in either labor rates or capital equipment costs, none of the alternatives to the conventional manual process would be economical for the smallest concrete contractor participating in this study, as the capital costs that are required represent a sizable investment (minimum $167,500 or four times the amount required for the

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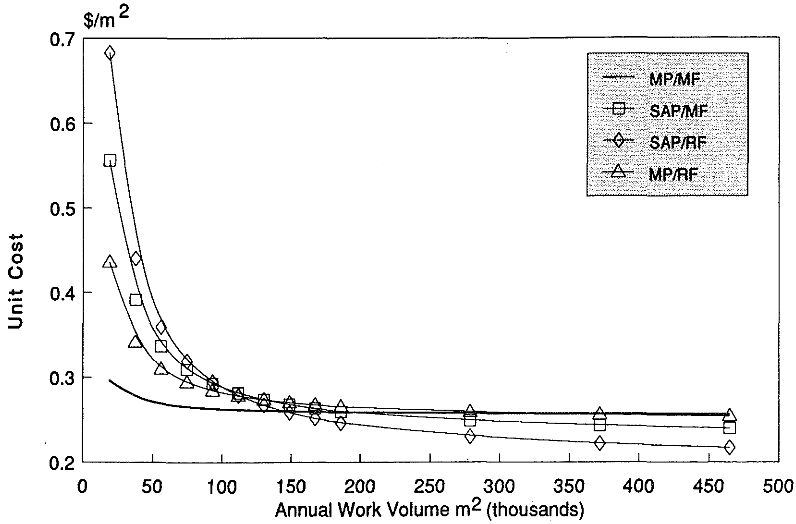

FIG. 3. Unit Cost of Various Levels of Automation for Conventional Slab

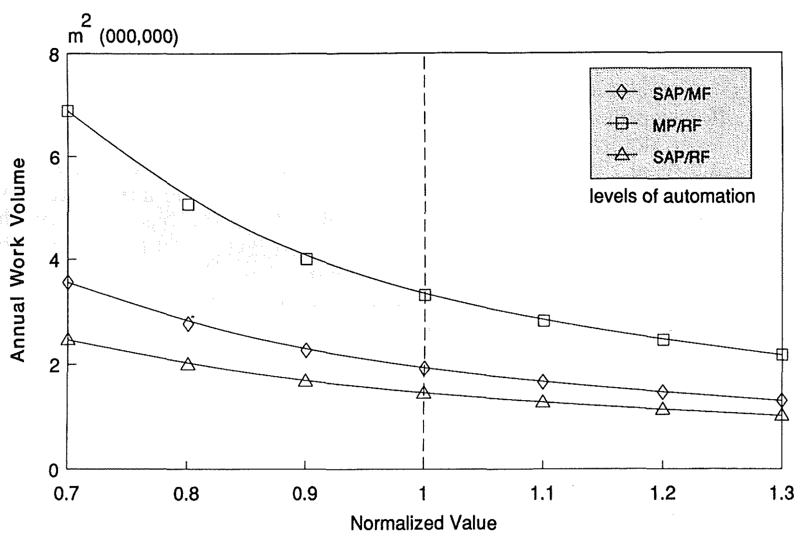

FIG. 4. Effect of Labor Rate Variations on Break-Even Volume of Work

conventional manual process) and the annual volume of work that must be achieved represents a large amount of business (minimum 126,825 m^2 [1,400,000 sq ft]). A medium-large firm would certainly find the required investment and work volume less difficult to achieve.

Of the three alternatives, automation of both placing and finishing requires the lowest annual volume of work to be as economical as the conventional manual process, but requires the greatest capital investment. The greatest benefits are achieved by reducing the overall duration of the process

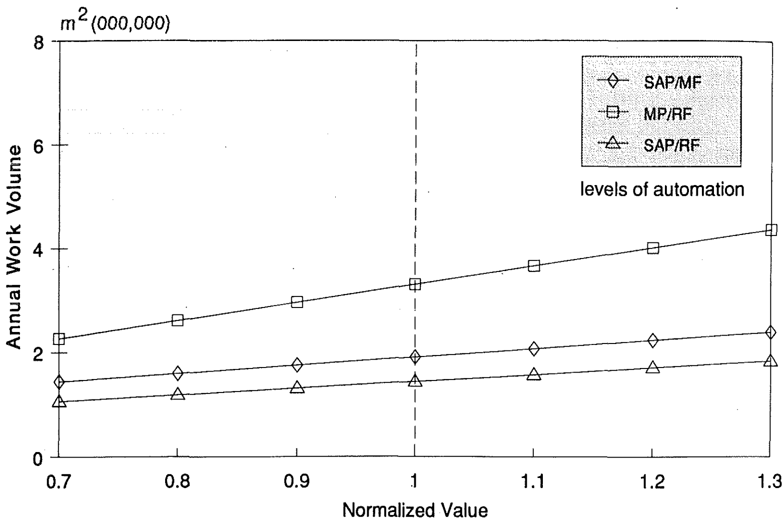

FIG. 5. Effect of Capital Cost Variations on Break-Even Volume of Work

by 5 hours (60%). Crew-size reductions result in labor savings of four men (33%) during placing operations but are slightly offset by an increase in the finishing crew of 1.5 men (25%). The fully automated process was also found to be less sensitive to variations in labor rates and capital equipment costs than other levels of automation.

At 191,030 m² (2,100,000 sq ft) per year, the automation of placing alone was found to be economical well within the actual annual volume of work of the contractor using it. Benefits were incurred through labor savings of four men (33%) in the placing crew, and a reduction in activity duration of 2 hours (20%). Additional savings could be obtained if screeding of edges around the perimeter of the slab could be eliminated. Automation of finishing alone is the alternative that requires the greatest volume of work to be more economical than the conventional manual process because the robot's use is restricted to troweling, and its production rate is limited by that of the placing operation: the benefits in this case were obtained solely by a reduction of 30% in the size of the finishing crew.

Quality Considerations

A main assumption of this analysis is that unless a client explicitly specifies a high surface-quality slab, the contractor is unable to charge for the quality improvements resulting from automated placing because of reciprocal competition. What would be the value, however, of semiautomated placing when compared with the manual construction of a similar-quality slab?

In order to answer this question, the construction of an F_f45/F_l30 unit slab is modeled based on the same parameters as the base case conventional slab, taking into account the following changes: the unit slab is constructed by pouring alternating 6 × 62 m² (20 × 200 ft²) strips, with three strips poured on the first day and the remaining two on the following day. A 16-man crew is required for the operation, of which eight are used for placing with a mechanical straightedge, two for manual restraightedging, and six for manual floating and troweling. Forming costs are considered based on

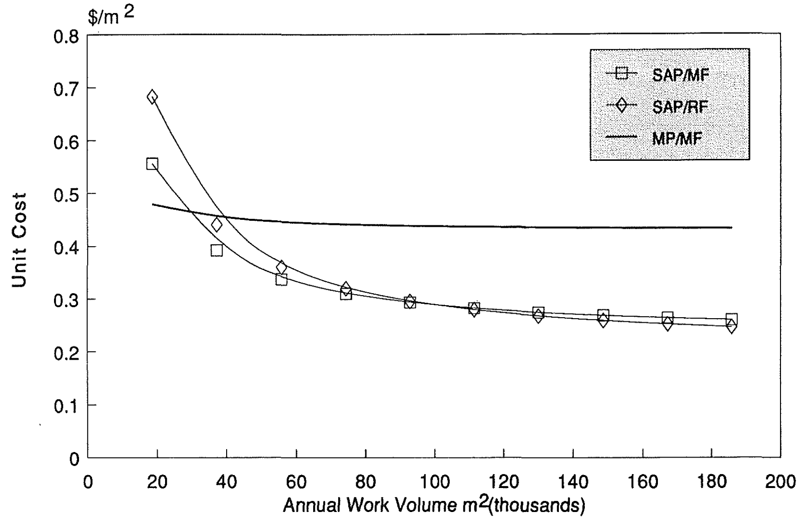

FIG. 6. Unit Cost of Various Levels of Automation for F_f45/F_l30 Slab

a crew of two carpenters and four laborers for a full day at a cost of $28.08 per hour and $17.60 per hour, respectively.

The results, shown in Fig. 6, indicate that when considering the construction of an F_f45/F_l30 slab, an annual volume of work of 27,885 m^2 (300,000 sq ft, or 15 unit slabs) is required for automation of placing alone to be more economical than manual construction, and 39,039 m^2 (420,000 sq ft, or 21 unit slabs) are required for the automation of both placing and finishing. Both SAP/MF and SAP/RF allow a reduction in activity duration from 12.5 hours over two days to, respectively, 8 hours and 4 hours in one day, and a reduction in manpower from 16 men over two days to 14 and 15.5 men in one day.

Summary and Concluding Remarks

In view of the current state of construction automation and robotics, contractors may have to integrate various levels of automation in order to achieve operational objectives. The study indicates that slab-on-grade construction is a sequential process necessitating a constant production rate during concrete delivery, placing, and finishing. In order to produce benefits, a production rate increase in any one operation requires a similar increase in the others. The constraining factor to the automation of either placing or finishing alone was found to be the availability of labor to increase the production rate of the dependent operation.

Based on the survey results, conventional manual construction of a typical unit slab (1,859 m^2 at 150 mm; 20,000 sq ft at 6 in.) is accomplished in 10 hours with a 12-man placing crew and a six-man finishing crew. Automation of finishing alone was found to offer benefits through labor savings during finishing (30%), which requires a significant annual volume of work to be more economical than the conventional manual process (330,911 m^2; 3,600,000 sq ft), and therefore may not be accessible to small contractors. Automation of placing alone, offering benefits through labor savings during placing

(33%) and activity duration reduction (20%), was found to be more economical at 191,030 m^2/year (2,100,000 sq ft/year) when compared to a manually constructed conventional slab, and 27,885 m^2/year (300,000 sq ft/year) when compared to a manually constructed slab of similar high quality. Automation of both placing and finishing offers the greatest benefits, through labor savings (14%) and overall schedule compression (60%), since the increased production during automated placing can be fully absorbed by robotic finishing. It was found that 144,321 m^2/year (1,600,000 sq ft/year) were required for the fully automated process to be more economical than a conventional slab constructed manually, and 39,039 m^2/year (420,000 sq ft/year) when compared to a similar high-quality manually constructed slab.

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