Evaluation Method for Robotics Implementation: Application to Concrete Form Cleaning

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1 Summary

This paper introduces the concept of economic feasibility analysis for construction robotics using the examples of simple cleaning and maintenance tasks. A preliminary analysis of roboticized concrete form cleaning is performed. The *Net Present Value* of the contractor's investment in such a robot is estimated. The authors believe that the introduction of robotics to form cleaning may prove economically and technically feasible.

2 Introduction

The underlying purpose of this paper is to examine the engineering economic feasibility of introducing robotics to selected construction-related processes representing large volumes of repetitive work. The motivation for this work does not come at the present time from an absolute certainty that the introduction of robots to most construction-related applications will be immediately feasible. There is an obvious precedence of *technical* feasibility before a new robotic solution to the problem can become *economically* feasible. Satisfying these two conditions simultaneously is a necessary prerequisite for the successful introduction of robotics to any type of a construction process. However, we should now examine the possibility of using robots in construction in the future and be ready to implement them when the economic advantages of robotization appear. Therefore, it is important at this stage to consider an evaluation methodology for robotic solutions that are just now or will be technically feasible in the future.

A new approach to the evaluation of the impact of robotic technology on construction activities can

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be reflected in a **multi-dimensional framework** for the analysis of each possible application. Robotics applications to civil and building works can be divided according to several criteria, reaching in four different dimensions:[3]

1. The first dimension provides a distinction between various levels of the robotics impact on all construction activities, i.e.
   a. Direct robot substitution for human and/or powered machine labor in construction
   b. Extension of existing engineering practice due to the introduction of construction robotics
   c. Redesign of the current technological and organizational solutions and introduction of new, robotics-inspired processes.
2. The second dimension deals with levels of the construction activities which may be affected by robots. The following levels are taken into account:
   a. Individual work procedures, e.g. elements of surveying, finishing works, etc.
   b. Construction of structural subcomponents, e.g. foundations, building frames, partitions, etc.
   c. Entire structural and construction systems.
3. The third dimension provides for a distinction between the implementation of robotics in proximate and in off-the-job-site applications. Proximate and Off-Site robot applications have the advantages of not requiring mobility and enabling better control of a robot's local environment.
4. The last, fourth dimension of our analysis will be represented by a continuous time variable, since robot technology, with respect to both hardware and software, experiences a rapid advancement.

This paper concentrates on one aspect of maintenance operations involving the cleaning of reusable concrete forms. The authors evaluate the possibility of developing a robot assisting a human worker in cleaning and oiling of forms used in the erection of concrete foundation walls. The main objectives of the cleaning of forms are presented in Figure 1. For this preliminary analysis, only a subset of the various dimensions defined will be treated.

One reason for this application selection is the fact that concrete formwork costs often comprise up

[3]See M. J. Skibniewski: Feasibility Analysis of Robotics in Construction Applications, Ph.D. Thesis (in progress), Dept. of Civil Engineering, Carnegie-Mellon University, Pittsburgh, PA.

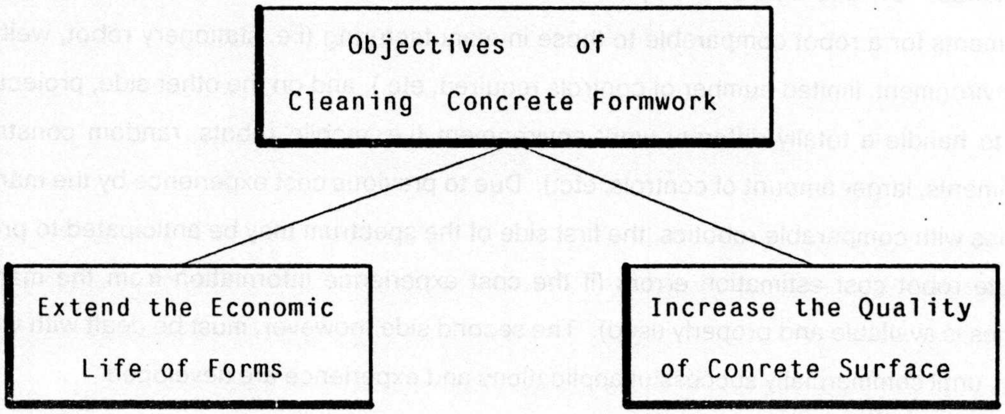

Figure 1: The Purpose of Form Cleaning.

to 30 to 60 percent of the overall cost of concrete work on a construction job,[4] and their maintenance is often a significant portion of these costs. Another reason is the fact that the increased maintenance can extend the life of forms and create additional cost savings to the contractor.[5] These facts may be seen as incentives to look for alternative solutions to at least some of the costly formwork-related procedures. Supporting the selection of this application is the fact that most manually performed cleaning and oiling tasks are very simple and relatively unattractive for a human worker.

Despite the simplicity and unattractiveness for humans, the work may be quite challenging for a robot. Before a successful robotic replacement can be designed, a detailed and robot-oriented analysis of this work process is necessary.

3 General Comments on Robot Cost Estimation

Although the issue of cost estimating of a construction robot work system is very important for engineering economic analysis, it is very difficult. This difficulty comes from the fact that no successful commercial applications of construction industrial robotics have yet been developed in the United States. As implied before, there is a possibility of a substantial, uncontrolled error in such an estimate for any type of a construction robot. One can, however, classify errors in the robot cost estimation on a rational basis, according to the level of uncertainty in the robot component

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[4]J. Christian: Management, Machines and Methods in Civil Engineering, John Wiley & Sons, 1981.

[5]For example, a typical wall forming set manufactured by *Western Forms, Inc.* costs on the average \$108. per m^2 of the forming surface in 1985 and can be reused approximately 15 times.

performance. On one side of the spectrum, one can place construction robotic projects with the requirements for a robot comparable to those in manufacturing (i.e. stationery robot, well structured work environment, limited number of controls required, etc.), and on the other side, projects requiring robots to handle a totally different work environment (i.e. mobile robots, random construction site environments, larger amount of controls, etc.). Due to previous cost experience by the manufacturing industries with comparable robotics, the first side of the spectrum may be anticipated to produce only moderate robot cost estimation errors (if the cost experience information from the manufacturing industries is available and properly used). The second side, however, must be dealt with with extreme caution, until commercially successful applications and experience are developed.

The robot cost estimation below should be associated with the first side of the cost estimation spectrum, since it represents the type of application somewhat resembling a factory environment, although the work process is conducted on a construction site. Therefore, a satisfactory degree of reasonability and accuracy should be expected from the estimation methodology and its results.

3.1 Assumptions For a Simplified Economic Analysis

The economic analysis of the robot applications to the stated construction work task can, as stated before, reach in many dimensions. The more complex the work task, the more dimensions must be addressed, and, probably, the more simplifications and arbitrary assumptions must be made. The amount of these arbitrary assumptions can be substantially reduced as soon as reasonable cost and price fluctuation data becomes available. This, in turn, will require comprehensive handling of the amount and quality of data reaching in many dimensions. In our case of the form cleaning robot, the number of these dimensions is relatively small.[6]

In brief, the following assumptions are being made in the benefit and cost analysis of the case study of roboticized form maintenance:

1. Benefits and costs derived from the robot operations are accrued continuously, but are accumulated at the end of each construction season.

2. Labor cost, as well as the cost of tools, materials and supplies remains constant in real terms over the economic analysis period (assumed as 5 years to coincide with the expected life of the robot).

3. Applied robot hardware and software solutions will remain relevant and robot productivity will remain constant over the assumed analysis period.

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[6]Computer-aided handling of cost and benefit data and their analysis with a standard spread-sheet program will be feasible.

4. Formwork (and subsequently concrete wall surface) quality improvement derived from the implementation of the form cleaning robot can be quantified and will remain constant over the analysis period. For the sake of simplicity, it will be assumed in this case study that the work quality total benefits will constitute 20% of the formwork erection cost.[7]

5. The number of projects per season will remain constant during the analysis period (5 years).

6. All replaceable hardware (i.e. robot arm end effectors) will remain in usable condition throughout one construction season regardless of the number of projects performed in that season.

7. All projects performed during the analysis period are similar in quantity of work per project and in the technical difficulty of the task.

8. Power supply, work service, robot downtime, and robot transfer/reinstallation costs are directly proportional to the number of projects performed in a construction season.

If reasonably accurate technical and financial information is available, most of the above assumptions can be disregarded and constraints released for any individual case study or set of projects. It will increase the level of complication in presenting the economic analysis, but this difficulty could be overcome by simulating different solution alternatives and by the use of a computerized financial analysis.

3.2 Cost of Research and Development

It is extremely difficult to predict research and development (R&D) costs of the new robotic equipment that will prove satisfactory in field performance as well as cost effective. Instead of undertaking a basic effort to rationalize the future research cost and to quantify its individual components, it will be more reasonable to compile existing experience of developing robotics for the U.S. manufacturing industries. Moreover, to further simplify the robot economic analysis procedure, contingency values of R&D efforts may be incorporated into the anticipated costs of component implementation in the designed robot. This approach will be adopted for the subsequent initial analysis of the anticipated cost of the form cleaning robot.

The research and development costs of the form cleaning robot can be divided into the following categories:

1. Adjusting and upgrading of existing industrial robotic components to meet the

[7]The value of savings on work quality improvements must be carefully estimated for every specific work application. Direct and indirect savings must be considered. The outline for estimating the savings from work quality improvements is presented later in this paper.

construction work site environment. This cost figure will presumably constitute a major portion of the total R&D cost.

2. Software development costs. New software for running the control procedures for the robotic arm and the effectors will represent a significant investment. Basic algorithms can presumably be adopted from the software for existing industrial robotics.

3. Costs associated with basic research and development of prototypes for individual components of the Form Cleaning Robot. These costs are associated with entirely new components for the Form Cleaning Robot which do not have predecessors or close prototypes in other industries. In this case, these costs should be regarded as relatively small, due to the similarity of the performance specifications for this robot to those of manufacturing robotics.

4. Miscellaneous R&D costs. This figure is to include additional development considerations not directly associated with the design and implementation of the Form Cleaning Robot itself. For example, it may entail costs of development of a portable form cleaning work station, design of a robotic tool pallet, etc.

4 Operations Involved in Cleaning and Oiling of Forms

The regular maintenance of concrete forms has the following tasks (see figure 2):

1. To remove debris and remnants of old concrete from the surface of forms. This is done to provide a smooth contact surface between the concrete mix and the inner area of form in the next pour.

2. To distribute a thin layer of oil or other chemical agent over the inner side of form's surface. This is performed to ensure a better outcome of the form stripping process.

3. As secondary tasks, handling (e.g. positioning) and transportation of forms to and from the construction erection site must also be considered. This also involves issues such as form storage, repairs, etc.

The combined result of the above procedures is better quality of the next produced wall surface and longer economic life of the reusable concrete forms.

The following operations are involved in cleaning and oiling of stripped concrete forms (see Figure 3):

1. Positioning of forms on the cleaning stand. This operation is usually performed by two laborers, often with the aid of a mobile fork lift if the weight of forms exceeds 100 kG. They are brought from a nearby stack of stripped forms, picked up and dropped manually, or with the help of a fork lift.

2. Washing of forms with water. This is a relatively simple process which requires an uniform application of a pressurized water stream of approx. 250 kPa on the entire surface of form. It is normally performed by one laborer.

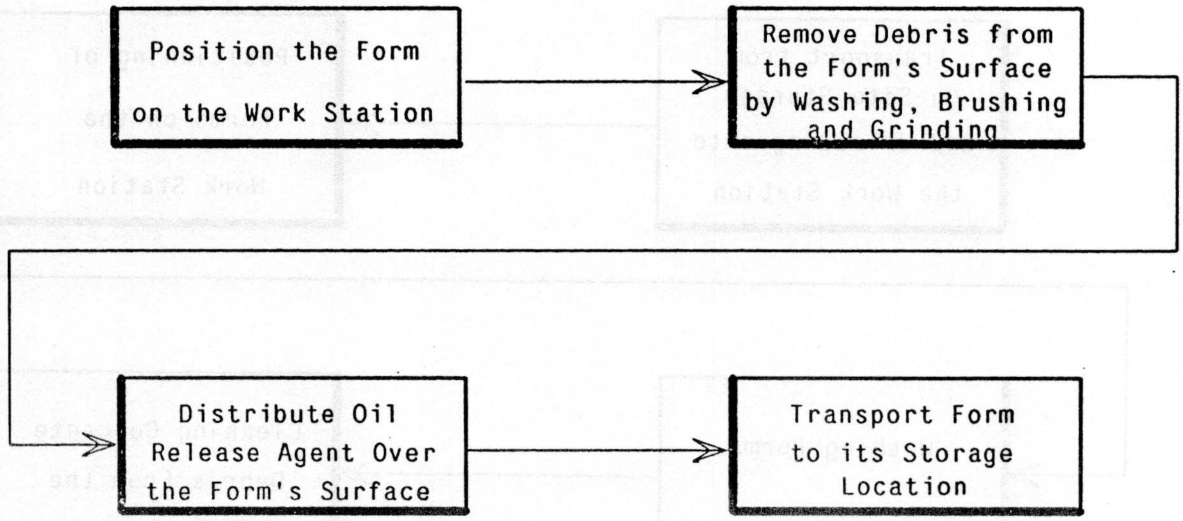

Figure 2: Tasks Involved in Cleaning and Oiling of Forms.

3. Scrubbing the remnants of concrete mix from the form panels and frames with chisels and wire brushes. This process requires a variable input of effort and depends on the quantity of concrete remnants on the form surface. Since the quality of the next constructed wall surface depends mainly on this operation, particular attention should be given to the outcome of this work. One can assume that in a continuous cleaning process there are two laborers assigned to perform this work.

4. Applying a uniform coat of oil (or other chemical) agent on the form panel surface. It is usually performed by one laborer carrying an oil container and a soft brush. He must ensure that the entire area of a form exposed to concrete is covered with the agent.

5. Transferring the forms to their storage location. This operation requires a similar effort to that of positioning. It is performed by one or two laborers with the help of a mobile fork lift.

The number of times that the above procedure is repeated on a single construction site depends primarily on the size of the project. Typically, the cleaning procedure on the same set of forms is performed once, twice, or three times, depending on the number of forms available for the project. On large project construction sites, however, the number of repetitions on the same set of forms can be larger. The cost of this procedure varies with the available maintenance equipment, the geographic region and the organization of work on the construction site.

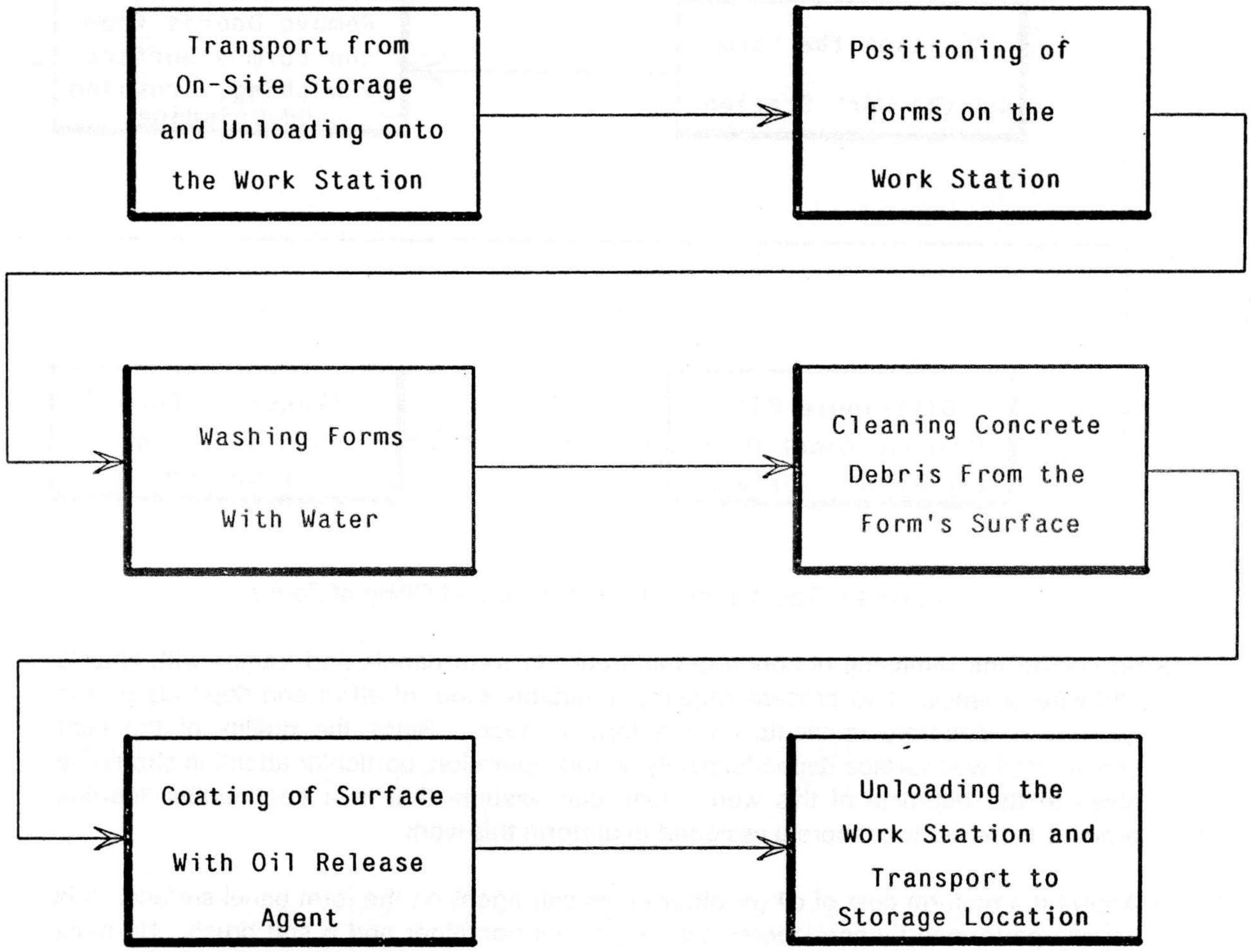

Figure 3: Operations Involved in Cleaning and Oiling of Forms.

5 Cost Analysis of the Manual Work Process - An Example

A summary cost analysis of the manual form cleaning process will be performed. The assumed construction project characteristics are believed to represent a typical environment of an erection of a medium-sized foundation wall of a typical industrial building. It is anticipated that construction sites of such buildings (with respect to the foundation erection techniques) may prove to be a relatively congenial environment for a partial automation and robotization of work operations, due to large volumes and the relative simplicity of individual work tasks.

The cost data for the formwork cost analysis are compiled from publications and advertisements by the reusable concrete formwork systems industry in the United States. Labor input requirements are derived on the basis of a comparison between various formwork systems and traditional labor input quantities with respect to a form cleaning task.

For the purpose of exposing the cost estimation procedure itself, rather than its intermediate and final numerical outcomes, all the quantitative entries in the procedure will be parametrized. This will make it possible to later verify the entries and adjust the quantities and unit costs according to local and updated data adopted from the area of application interest. The outcome of this project's form cleaning cost estimating procedure will be used in the subsequent economic analysis of the robotic replacement of manual labor.

5.1 Estimation Procedure

A rectangular foundation wall will be assumed. The dimensions of this foundation plan reflect typical parameters of a simple industrial building foundation. Let us assume that the height of rectangular foundation wall elements is 150 cm (1.5 m). The above dimensions imply the needed total area of the wall formwork:

$$S = 2 \times 2 \times (100 + 60)\, m \times 1.5\, m = 960\, m^2.$$

Data regarding time requirements for the manual form cleaning process can be obtained from field observations. According to the author's observations, however, this time length (t_{fc}) can be estimated for approximately 10 min. per 1 m^2 of the form surface. The total time required for the cleaning of forms used on this example project (T_{fc}) can be estimated as

$$T_{fc} = S \times t_{fc} = 960\, m^2 \times 10\, min./m^2 = 9600\, min. = 160\, hrs.$$

(i.e. 20 full work days with one laborer, or 10 days with two laborers)

Total labor cost for the cleaning the forms on this project (LC_{fc}) equal to:

$$LC_{fc} = lc_h \times T_{fc} = \$15./hr. \times 160\, hrs. = \$2{,}400.$$

The above amount does not include indirect costs (e.g. supervision, repairs, etc.)

Also, the cost of tooling and equipment should be considered. The items to be included are:

- Cost of scrubbing and grinding tools
- Cost of oil release agent for the coating of forms
- Cost of water and miscellaneous supplies

According to field experience, it can be assumed that currently used manual grinding and scrubbing tools may be effectively used (if properly maintained) for approximately 160 hrs. of their worktime (with no salvage value). The market price of a hand-held electric grinder is approximately $200.

The cost of oil agents suitable for formwork release applications varies, depending on the quality and chemical structure of the product. It is assumed that the cost of the applicable chemical is comparable with the cost of ARCAL LIQUID "SW-248 MET" - a protective barrier coating used to prevent concrete buildup. A vendor's price is approximately \$4. /dm^3, the approximate usage is 0.33 dm^3 per 1 m^2 of formwork; thus requiring a contractor's expense of \$1,280 per 960 m^2 of formwork.

The water supply is assumed already in place, so only the form maintenance-related water usage cost will be considered. The water consumption can be assumed in the amount of 16 dm^3 per 1 m^2 of forms at a cost of \$0.75 per 1000 dm^3 of water. Thus, the total water consumption cost for this project will amount to approximately \$12.

Miscellaneous tools and equipment contingency cost is meant to provide a provision for additional expenses associated with the equipment maintenance or scheduled repairs. It is assumed here in the amount of \$50.

According to the analysis presented above, the total form maintenance cost for the duration of the project is accumulated in table 1.

Maintenance labor cost	\$2,400.
Tooling & equipment	
- oil agent	1,280.
- grinder	200.
- water	12.
- misc. tools, etc.	50.
Form maintenance handling	480.
Total (approx.)	\$4,400.

Table 1: Total Form Maintenance Cost Per Project (With Manual Labor).

The share of form maintenance cost in the total labor cost of erecting and maintenance of forms is about twenty five percent.[8] The ratio expressing the contribution of form maintenance labor cost to the total cost associated with the use of formwork is approximately 15%. Both values of 25% and 15% indicate a considerable cost associated with the cleaning operation. Considering the underlying construction cost savings potential, preliminary decision-making criteria for undertaking efforts to automate the cleaning of forms (or other suitable tasks) could be based on the values of those parameters.

[8]See M. J. Skibniewski, op. cit.

6 Information Required for the Design of a Robotic Replacement

The information contained in this section appears as necessary background for subsequent design of robotic assistance or replacement. It is an engineering and ergonomic analysis of the work process under investigation, and does not imply that all individual subtasks contained and analyzed herein are immediate candidates for robotization. Rather, the analyzed operations are scrutinized for their complexity, repetitiveness, and rigidness of the work environment. The decision whether to attempt the robotization of a specific operation or to leave it as human-operated and controlled can be made according to the previous development experience and best engineering and economic judgement.

The information flow process during the performance of the cleaning process appears simple and straightforward for a human. There are a number of simple issues, however, that would have to be considered individually by an algorithmically structured working device resembling the human-performed decision process. A general cleaning process algorithm is presented in Figure 4 .

6.1 Positioning of Forms

The concept of roboticized or teleoperated positioning of parts has been already addressed in the manufacturing industries with respect to small objects with total weight usually not exceeding 10 kG. These successful applications of the roboticized part positioning may provide guidance for robot-aided positioning of concrete forms onto the cleaning stand.

The positioning of forms involves a basic skill of being able to place a form or a set of forms on the cleaning stand. The following information would be needed for an automated robotic machine to perform the positioning task:

1. Shape and dimensions of the cleaning mat. Usually, one deals with rectangular shapes, although other configurations are also possible. The four corners of the mat location must be specified and their coordinates must be referenced with respect to an established reference location and orientation. In the case of other geometric shapes of the stand, the approximate shape must be detected by touch or range sensors and recorded into the robot memory for further reference.

2. Weight of the forms and their shape. The information regarding the weight of forms and their mass distribution is useful in determining the dynamic factors (such as inertia forces) affecting robotic handling of forms. The information pertaining to the geometric shape and mass distribution of the form is necessary to design the anchoring locations on the surface of form for the sake of safety and dynamic stability during the form transportation and handling. This information is also useful in the design of appropriate grippers.

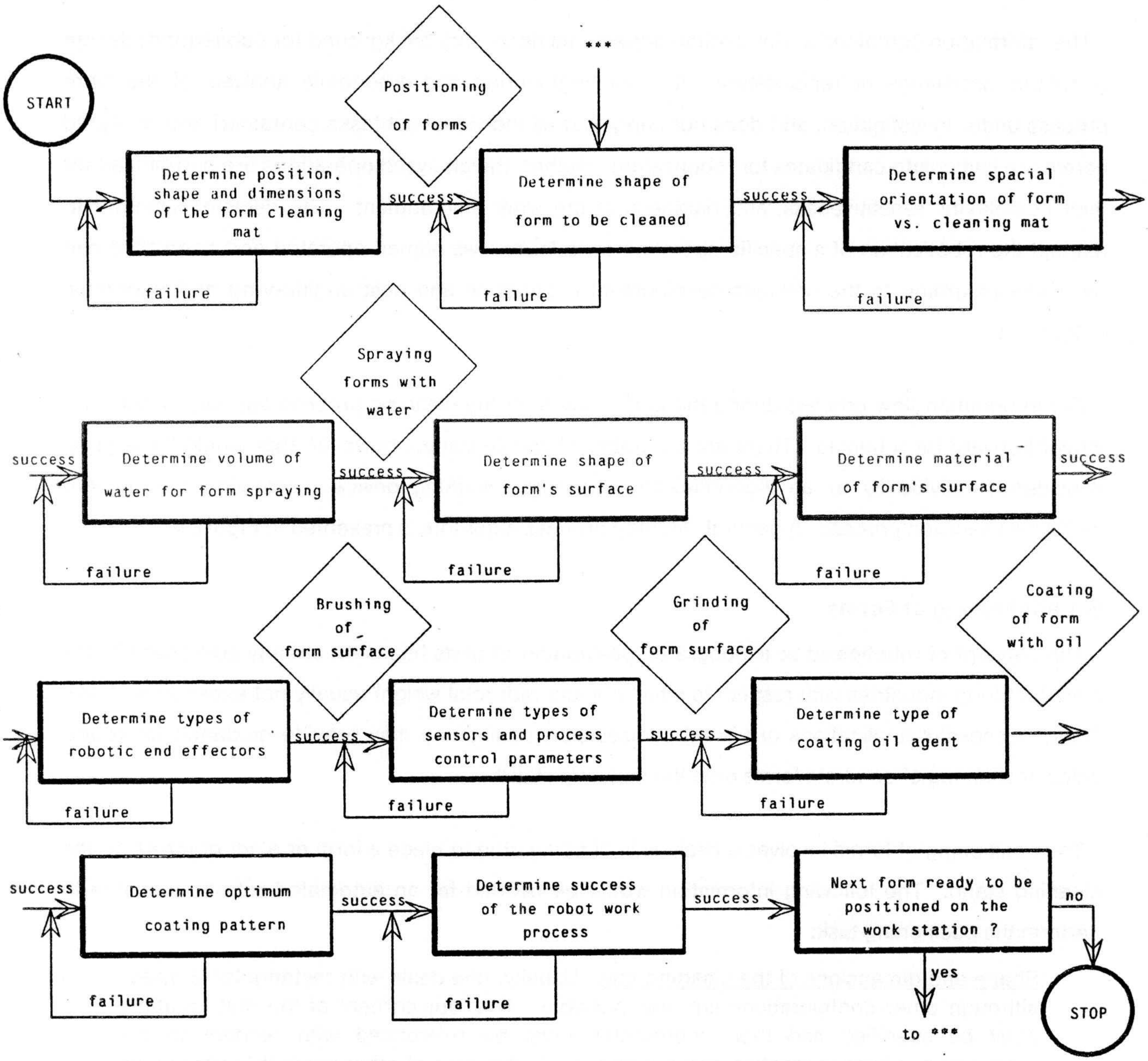

Figure 4: The Form Cleaning Process Algorithm.

3. Shape vs. space orientation of form. The information regarding spacial orientation of a form is necessary to place it correctly on the cleaning stand. This information must be conveyed to the robot's memory through a set of sensors detecting the form's position with respect to the position encoded in the robot's memory as 'correct.' If the actual handling position is determined by the robot's on-board computer as 'incorrect,' special

handling routines must be invoked, or human assistance should be requested.[9]

The following changes to the form specifications would be anticipated as necessary to enable the robotic handling of forms from their stacks to the cleaning stand and back to the stacks:

1. The shape and construction of form (e.g. mass distribution) should be scrutinized with safe and efficient robotic handling in mind as a design criterion.

2. The forms should be provided with gripping hooks detectable by intelligent proximity sensors mounted on the robot's arm.

The complexity of the above task with respect to handling environment and the amount of information to be handled does not qualify the handling of concrete forms as an immediate candidate for commercially successful robotization.

6.2 Washing Forms With Water

The problem of washing of forms with water with the aid of a robot is very similar to the robotics application in other industrial tasks involving paint spraying. These previous similar applications provide the initial technical feedback for the robot application to washing of forms with water.

Although this task does not seem to be particularly challenging if compared with other tasks involved in this application, one must still collect a variety of information for the successful execution of the task by a robot:

1. Dimensions and shape of form. This information has been already discussed for the design of the robotic handling of forms. At this point, one is interested in the shape and dimensional details which affect the successful washing procedure designed for the form surface. For example, small and hidden confined areas should be given particular attention by the robot arm during the execution of the washing sequence (e.g. applying the stream of water from a closer distance, adjusting the spraying angle to reach confined areas, etc.).

2. The correct sequence in which spraying with water is to be performed. The robot arm is to be servo-controlled, so a set of coordinates for the key points on the form's surface must be entered into the robot memory. The sequence should ensure that remnants washed away from one location on the form's surface do not subsequently accumulate in another location, and thus never get washed away from the form. The optimum sequence should also ensure economical use of water.

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[9] As a simplifying alternative, it could be required that forms be stacked in an appropriate order and in a strictly determined location. Such a condition might save a considerable sensor control and computation effort, but would also impose additional requirements on human labor and supervision.

3. Source and required volume of water. The volume of water can be obtained from already available data regarding the water pressure and the area of forms to be washed.

There will be some changes to the design of the cleaning stand and of forms resulting from the washing procedure performed by robotics. One important consideration is that the source of water is located nearby, so it is easily accessible by the robot's arm. One provision required for the roboticized washing of forms is the installation of a valve mechanism suitable for operation by the robot arm. The sewage arrangement is also important, particularly with large amounts of outflowing water from the spraying process.

6.3 Brushing and Grinding

This operation is essential in the manual form cleaning process, because it is expected to provide a smooth finish to the form surface as its final outcome. However, as will be described later, this work task will be eliminated in the robot-performed cleaning process. A considerable amount of information obtained from both the form design and from the sensory inputs would be required for the completion of this task:

1. The shape of the form surface. The shape information is needed for the same reasons as with the 'Water Spraying' task. The arm leading a corresponding manipulator through the form's surface would be servo-controlled. Critical points constituting the pattern of the manipulator's motion should be well defined.

2. The type of the form's surface. This information is important for the selection and setting of the robotic effectors applicable to this task and for the interpretation of sensory feedback during the execution of the task. For example, a soft brush and a poliurethane grinder could be used on a plywood form surface, but a wire brush and a steel grinder are applicable as the robotic end effectors on a steel or aluminium form panel. Also, different sensory output interpretations of the brushing and grinding process would be applicable for different types of surface materials. This sensory output would be in turn a critical factor classifying the outcome of this work as *'acceptable'* or *'rejected'*. The latter negative outcome of the decision made by the on-board computer would result in the repetition of the preprogrammed brushing and/or grinding sequence until a satisfactory result is determined by the manipulator sensors.

3. Types of applicable effectors. Particular attention should be given to a proper selection of the applicable effectors. It is assumed that the interchangeable effectors can be stored in one location, easily accessible by a robot arm. A practical solution for the tool storage and retrieval by an automated procedure must be designed. Brushes and grinders would have to be selected in such a way that the maximum smoothness of the form panel surface is obtained. The robot arm manipulator would have to have at least 5 degrees of freedom to account for predictable tool maneuverability requirements.

4. Types of applicable sensors. Several sensors would be necessary to continuously monitor the outcome of the brushing and grinding procedures. The quality of work

determines a need or lack of need for improvement in outcomes from this work. It is necessary to obtain a smooth surface finish as a final result. It may be assumed that the condition of surface could be monitored by contact sensors or range sensors.

6.4 Coating Forms with Release Agent

Similar control and sensing information as for spraying forms with water applies also with regard to the control and sensing during the coating of forms with a form release agent. The additional information that must be taken into account is the surface thickness of the oil agent spread over the form. This parameter would have to be assured by the coating pattern algorithm in the robot memory. Other detailed issues, such as consistency of the agent, its temperature, viscosity, and other parameters must be also considered for a successful robotization of the coating process.

6.5 Storage of Clean Forms

Storage of clean forms requires an equivalent amount of information and control procedures as the handling process described above. Forms must be transported from the cleaning work station to their storage location near the next application side. The transport and storage processes are in themselves issues requiring a large amount of mobility and control capacity, and therefore quite involved. For the reasons stated previously, it is assumed that this process is not an immediate candidate for a commercially successful robotization and should be handled with human assistance and supervision.

7 Proposed Design Specifications for the Form Cleaning Robot

Experience with automated cleaning procedures in other than construction industries indicates that the cumbersome manual cleaning process can be reduced to **high pressure (700 kPa) water-jetting** of the form surface. Examples of successful applications of water jet cleaning can be found in several branches of industry other than construction.[10] Their experiences indicate that one can also expect satisfactory results from applying the water jet for the removal of concrete remnants from concrete formwork.

In brief, the form cleaning robot will perform the following operations:

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[10]For example, robotic cleaning of aircraft fuel tanks at the *British Aerospace*, Filton, Bristol (England). A Stationery Hazmac's Workmaster Robot operating a water jet cleaning nozzle was applied. In another instance, a non-servo pneumatically driven and automatically controlled robotic machine utilizes water jet stream to the cleaning of the interiors of nuclear power plant reactors (Polytechniques, Inc., Solon, Ohio).

1. The robot motors are activated and the arm moves to the end effector (tool) pallet to pick up the effector containing the water jet nozzle. The interchangeable end effectors are connected to the robot arm by quick disconnect bayonet sockets.

2. After a form is placed with the help of a fork lift on the work stand by a laborer, the water supply turns on automatically. The arm moves to its initial position over the form's surface and begins to move above the surface according to a predetermined uniform spraying pattern. The water pressure is kept constant throughout the duration of the spraying time. It can be, however, adjusted according to the cleaning requirements.

3. The arm subsequently proceeds back to the end effector pallet and replaces the water spray gun with an anti-adhesive spray gun. Then it moves back onto the initial position over the form's surface and begins a similar spraying process again.

4. After this anti-adhesive spraying operation is completed, the spray gun is placed back into the same pallet slot. Again, the water jet gun is reconnected to the robot arm. At each slot, one effector (i.e. spray gun) is connected to the arm's wrist through a quick disconnect bayonet socket.

5. The arm moves to the initial position over the form's surface and awaits the placement of another form onto the cleaning pad.

The following is a brief description of the requirements which must be fulfilled in the development of robot hardware components, as well as in assuring all necessary interactions between the robot system elements.

7.1 Robot Mobility Requirements

The process of cleaning of concrete forms can be, as implied above, a stationery work process. This provision makes it possible to consider a stationery robot suitable to perform this task. The experience gathered by the manufacturing industries in the development of stationery industrial robotics can be utilized.

Inside the work station, the robot will be required to perform a variety of standard motions. The following motions are required:

1. Rotation of the entire robot around the vertical axis of the robot base (1 d.f.)

2. Rotation of the robot's arm in the shoulder around the axis perpendicular to the arm's plane (1 d.f.)

3. Rotation in the arm's elbow around the axis perpendicular to the arm's plane (1 d.f.)

4. Pitch (1 d.f) and yaw (1 d.f.) in the arm's wrist

All of the above motions are necessary to support the robotic operations outlined above. The above mobility schedule implies a total of 5 degrees of freedom for the robotic manipulator and the robot's base.

7.2 Weight and Durability of Hardware

To facilitate frequent transfers to different job sites, the total weight of the basic integral hardware (excluding peripheral devices) should not exceed ca. 230 kg. The peripheral devices should be easy to disconnect from the robot, to ensure maximum efficiency in disassembly, transport, and reassembly of the robotic equipment. The weight distribution of the robot parts should ensure the maximum stability of the equipment during transport and operation. The center of gravity for the assembled robot should not move beyond an acceptable distance from the center of its base. Since the robot-supported handling of forms is not considered, the only anticipated external loads on the robot are the loads resulted from the operation of the end effectors on the form surface.

All individual components of the form cleaning robot must be resistant to outdoor weather conditions. One way to provide for such resistance is to develop additional insulating covers and envelopes for each individual component of the robot. Such envelopes should not, however, limit the utility and flexibility of the working equipment. Initial experience in this area has been gathered by several robot manufacturers for paint spraying applications.[11]

7.3 Robot Arm

The robot arm should be made of a lightweight hard metal or durable plastic material to provide for maximum rigidity and strength. The rigidity of the arm's material is meant to provide a high accuracy of the arm's motion, and the material's high strength is necessary to ensure the reliability of the arm's components under possible dynamic loads during the work process.

The arm must be equipped with two single and one double joint, giving it a total of 4 degrees of freedom. It is necessary that the joints be protected from dust and dirt, to assure their uninterrupted action during the work process and minimum required maintenance.

[11]For example, *BINKS Manufacturing Co.*; Robot System no. MK-II-90 and *Graco Robotics, Inc.*; Robot Systems OM 5000 and OM 5.

7.4 End Effectors

There are two end effectors that should be able to work with the form cleaning robot, i.e. two types of spray guns applicable to this work process. The first type connected to a source of water for water spraying of forms, and the second is connected to an oil agent container for surface spraying with a form release agent. To provide for proper functioning, the second gun must ensure proper consistency and temperature of the release agent.

7.5 Sensors

Due to the simplicity of the spraying process, no touch or proximity sensors for the form cleaning operation are required.

7.6 Control

Existing industrial robotic hardware control facilities should prove satisfactory, but additional research and development in meeting outdoor stationery robot work conditions may prove necessary. The cost and effort required for the development of satisfactory robotic hardware controls depends on the environment in which the robot is to work. Since reasonable estimates of these costs and efforts can be made by their extrapolation from similar robots in the manufacturing industries, it should be possible to estimate similar costs and efforts with regard to the form cleaning robot working on the construction site.

8 Cost Estimation of the Form Cleaning Robot

An accurate robot cost estimation task is very difficult. The accuracy of any such estimate must be viewed in the light of currently available technical and cost information regarding applicable robotic components and comparable existing robotic systems. Therefore, this preliminary cost estimate must be reviewed when more detailed reference cost information becomes available.

8.1 Cost of Adopting Existing Industrial Robotic Components

The following items are to be considered:

1. Motors and Actuators:

   The electronic actuators for the robot arm and the manipulators will constitute an integral part of the robot hardware system. Therefore, the types of actuators will depend on the type of other elements of hardware, and the cost of their implementation will be included in the total cost of hardware.

2. Robot memory:

The total amount of memory space required for the robot's successful performance is assumed in the amount of 0.3 Mbytes. The robot is assumed to be guided by a standard 68^K microprocessor with a 32-byte access by an operator. This access will provide for the possibility of on-site control of current work process by a human operator. The cost of implementing the required memory capability in the form cleaning robot will also be included in the cost of robot hardware selected for the on-the-site application.

3. End Effectors (Spray Guns):

The end effectors for the robot arm can be regarded as *special purpose hardware*, and must therefore be itemized as separate entities in the cost estimate of robot implementation.

As an example, the following water jet guns can be considered:

- "Spin Jet" Robot Cleaning System by National Liquid Blasting Corp. (Water Jet Cleaning Manipulator), or "Jetnife" Model # JN-65 (High Pressure Water Spray Manipulator)
- "Hydro-Powr" by Hydro-Powr Engineering Corp. (Water Jet Cleaning System)
- "AKR 3000" by AKR Robotics (Robot Manipulator with Water Jet Spraying Capabilities)
- Water Jet Manipulator by Accuratio Systems Inc. (Entire Robotic Work Cell for Water Jetting Applications)
- Jet Spraying Manipulator by Tokico America, Inc. Robotics Division (part of "Armstar" Automated Finishing System)
- "Model AA190A" Air Motorized Spray Washer by Spraying Systems Inc.

The purchase and installation costs of the above and similar equipment used in various branches of the manufacturing industries in indoor environments varies from $80,000. to $150,000., depending on scope and complexity of the cleaning task. Judging from the author's discussions with practicing engineers close to similar applications, the engineering cost of adjustment of such water jet cleaning robotics to the construction site rugged outdoor environment may approximately double the above cost.

The control function of the robotic end effectors is to be performed by the microprocessors whose cost is for the sake of simplicity already included in the respective hardware. Therefore, it is not presented here as a separate item.

4. The cost of programming and reprogramming of the user/robot interface must be estimated. An iterative method of estimate calibration may prove useful in the future. The following costs to the contractor are believed as reasonable, judging from interviews with robot system suppliers:

- Basic control software (i.e. robot system dependent software, low-level task descriptions, algorithms, etc.) - approx. $5,500.

- On-line programming and reprogramming, high-level task description, etc. - approx. $2,000.

The Basic Control Software Cost will be incurred once for each type of robot, whereas the On-Line Programming Cost will be incurred during each change in robot task specification. The On-Line Programming Cost can be estimated from previous user experience.

8.2 Cost of Initial Investment in the Form Cleaning Robot

The initial investment in the form cleaning robot consists of such items as: robot hardware, basic control software, robot memory, end effectors (water and anti-adhesive spray guns), and protective devices for sensitive elements of hardware. Vendors, however, usually do not break down the cost of the supplied system into individual items. It is customary for them to quote only a composite sum covering the hardware, controls, basic control software and memory configuration. Therefore, a composite sum covering these items will be provided in our example cost estimation.

An additional initial investment necessary to begin the robot operation on the job site consists of the following items:

- On-line programming (high-level user/robot interface)
- Initial robot on-site installation costs.

The total initial investment in the robotic equipment is presented in table 2. The estimates are based on the costs accrued on the installation of a comparable Graco OM 5000 Finishing/Spraying Robot in one of Sperry-New Holland manufacturing plants and modified after a comparison of the base environment with that of the actual outdoor construction site.

8.3 Annual Robot Operating Cost

The annual cost of robot performed form cleaning operations represents an operating expense which a contractor must incur to achieve the established form maintenance job objectives. This cost includes robot hardware depreciation, technical support service (equipment maintenance, inspection, etc.), on-line robot programming and re-programming, power supply, equipment downtime (for technical and organizational reasons), robot transfer to next job sites and hardware re-installation, and worn-out robotic arm end effectors. The yearly cost figures for the form cleaning robot are compounded in table 3.

With assumed reduction of 75% (typical industry estimate) in the required time for form cleaning, the total robotic cleaning time spent on the example project is reduced to 40 hours. Therefore, the estimated amounts for the Annual Operating Cost of the robot can be derived (see table 4):

Purchase and Installation Cost:	
Spraying Robot Complete with Pumps, Controllers, I/O Panels and Manipulators	$45,000.
Positioning Devices	5,000.
Freight for the System	1,800.
System Installation	20,000.
14-day Supervision of Vendor to Install and Start-Up the System	3,000.
Robot Peripherals:	
Additional Control Programming	4,000.
Robot End Effectors:	
Water Jet Gun	2,000.
Airless Electrostatic Anti-Adhesive Gun and Power Supplies	3,500.
Other Hardware:	
New Racks for the Feeding of Robot with Forms	4,000.
Spare Parts Kit	4,500.
Misc. Expenditures:	
Cost to Orient and Sort Sizes and Types of Forms	7,000.
Cost to Train Maintenance Operator	2,000.
Total Initial Investment (approx.)	$100,000.

Table 2: Initial Investment in the Form Cleaning Robot.

Robot Running (i.e. power, supplies, supervision, downtime, etc.)	$5./hr.
Equipment Re-installation	$ 2,000./work-site

Table 3: The Annual Operating Unit Costs of the Form Cleaning Robot.

Projects per Season	Cost of Robot Operation	Equipment Re-Installation	Total Annual Operating Cost
8	$1,600.	$16,000.	$17,600.
10	2,000.	20,000.	22,000.
12	2,400.	24,000.	26,600.

Table 4: Annual Robot Operating Cost with Respect to No. of Projects.

The individual items in the total cost figure can be verified and calibrated by an iterative process, when more accurate background information becomes available.

9 Estimation of Benefits Derived From the Implementation of Form Cleaning Robot

The utilization of a robot to the form cleaning task introduces at least two tangible sources of benefits to contractor:

- Labor cost savings: The savings are accrued due to the elimination of manual low-skill labor required to perform the cleaning task with manpower. There are however, increases in high-skill labor required, in "high-tech" software programming, hardware maintenance, and field supervision capacities.[12]

- Benefits derived from better quality of form maintenance: The planning engineer and the robot estimator must consult all relevant sources before outlining the quality savings estimate in project financial analysis. For this preliminary estimate of work quality benefit, a value of 20% of total foundation wall erection cost is assumed.

9.1 Estimation of Work Quality Improvements

Quality benefits derived from better maintenance and cleaning of forms can be assessed at several stages of the construction work process.

1. During inspection of the formwork before its reuse
2. During on-site implementation of forms
3. During quality assessment of the constructed foundation wall

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[12]This example indicates that although the volume of labor is definitely to be reduced, the implementation of robotics causes a need for high-skill professional labor. The "bottom line" consideration in this case is the labor cost savings, not reduction of human labor as such.

4. During planning and execution of subsequent construction activities.

Each of the above stages calls for a different method of work quality estimation.

- At the inspection of clean forms, quality indices (e.g. smoothness of form surface) can be introduced and expressed in dollar units ($). The quantification in dollar terms is based on the anticipated cost of form cleaning rework with manual labor.

- During the quality assessment of formwork on the wall erection site, eliminated concrete pour delays, unscheduled formwork repair and rework on improperly maintained forms can be quantified in terms of dollar savings ($). However, previous records within the company addressing these issues are necessary for comparison and estimation.

- On completion of the wall erection process, the quality of wall surface finish is to be assessed. The utility of surface quality outcome can also be measured in terms of dollars ($). With a good quality wall surface meeting the specification requirements, repair and patch work can be reduced or even completely eliminated. Previous work records regarding similar projects performed without roboticized equipment must be available for comparison and cost savings estimation.

- Cost savings derived from the elimination of delays of subsequent construction activities can be estimated on the basis of previous company records regarding the delays and their costs caused by inadequate wall surface finish (e.g. cost of delays in the placement of heavy water insulation, additional labor required to put the insulation in place caused by damaged underlying concrete surface, rework on the improperly placed installations in spite of unsatisfactory quality of wall finish, etc.)

All of the above stipulated cost savings can be expressed as a percentage of the total concrete wall erection cost. This fact can be used for an initial estimation of the project savings due to better quality of form maintenance.

The concept of methodology for the estimation of cost savings due to better formwork quality is presented in figure 5.

9.2 Simplified Quantification of Form Cleaning Robot Benefits

The economic benefits obtained from human labor savings are obtained by eliminating a considerable amount of unskilled labor required for manual operations in form cleaning. For estimation purposes, it will be assumed that all of the manual unskilled labor required for this task is eliminated by the robot. Form handling cost is not taken into account since the handling procedure remains unchanged and its cost remains similar before and after the robot application.

For the preliminary estimate of work quality benefit, a value of 20% of total foundation wall erection cost is assumed. This is a simplified assumed estimate of aggregate savings, which must be calibrated by an iterative process based on individual contractor's previous work quality experience and quality improvement record.

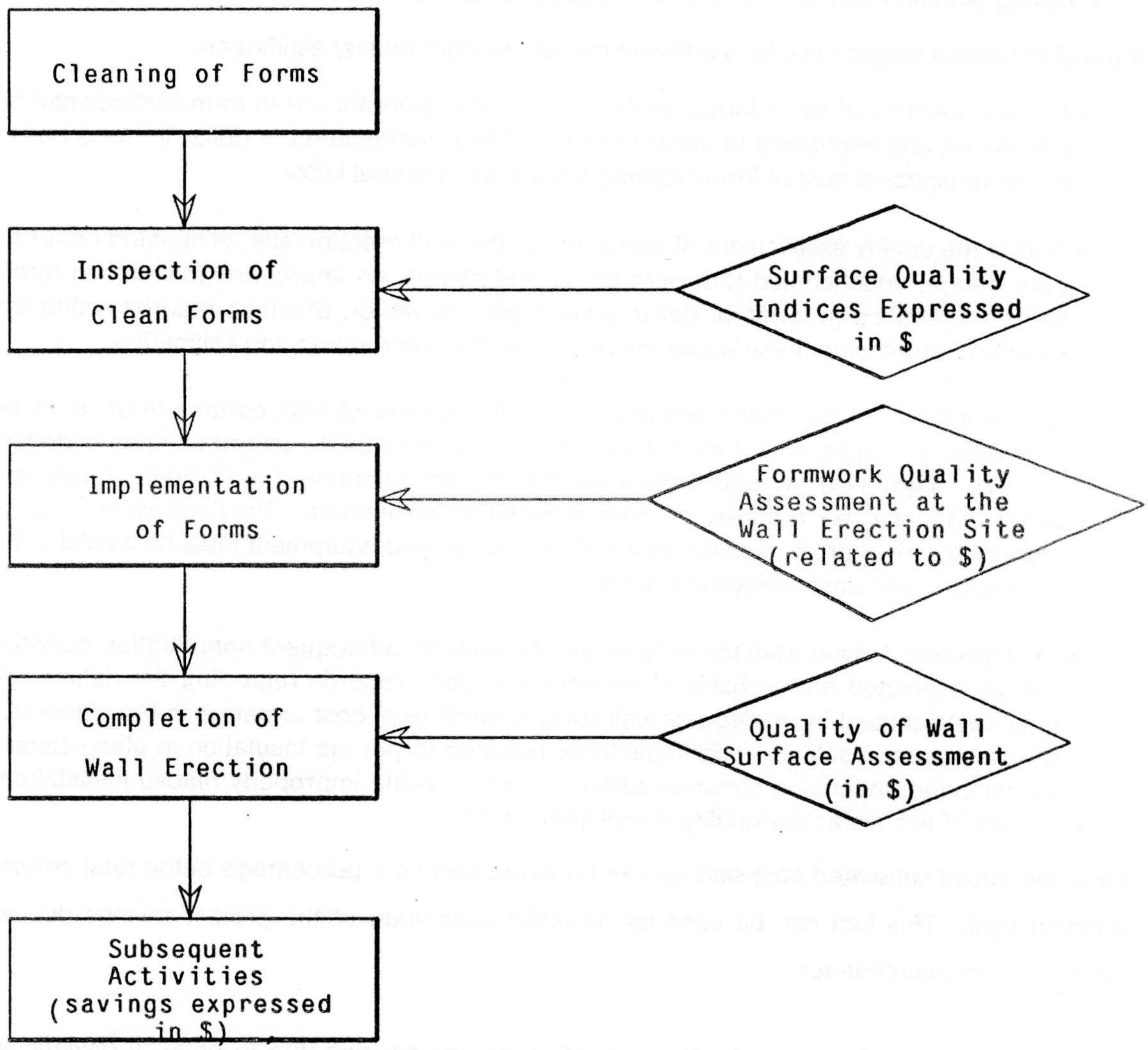

Figure 5: The Concept of Estimating the Savings from Better Maintenance of Forms.

The quantitative analysis of robot-introduced benefits to the example project is presented in table 5.

10 Analysis of the Net Present Value of the Investment and the Operation of the Form Cleaning Robot

The ultimate criterion of robot suitability for any operation in the industry is economic feasibility of its application. This feasibility may be expressed by several economic indicators. The most relevant

Projects per Season	Labor Cost Savings	Work Quality Savings	Total Benefits
8	8*$2,400=$19,200	8*$2,800=$22,500	$42,000
10	10* 2,400= 24,000	10* 2,800= 28,000	52,000
12	12* 2,400= 28,800	12* 2,800= 34,000	62,000

Table 5: Benefits Derived From The Form Cleaning Robot.

indicator, i.e. *The Net Present Value* of the robot investment and operation will be used.[13]

In our case the Net Present Value analysis will be based on the initial investment cost (IV) and on the uniform net benefit values due to the robotization project on an annual basis. The annual uniform net benefit (NUB) (called also the Annual Net Cash Flow) derived from robot operation can be obtained from the following formula:

$$NUB = RUB - RUC$$

where:

- RUB = total benefit derived from the operation of robot (shown in table 5)
- RUC = annual operational cost derived from the operation of robot (shown in table 4).

The annual net cash flows for the investment in the Form Cleaning Robot are presented in table 6.

Values of the Net Present Value of form cleaning robotization are presented in table 7. The positive figures represent a profitable investment, and the negative figures indicate projected net loss from the investment and operation of the form cleaning robot. The robot profitability depends, among other factors, on the level of its job-site utilization and on the discount rate (i.e. MARR) applied to the robot investment. The higher the level of robot utilization and the lower the discount rate, the more profitable investment in the form cleaning robot.

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[13]For discussion of this method, as well as alternative engineering investment analysis methods, see T. Au and T. P. Au: Engineering Economics for Capital Investment Analysis, Allyn and Bacon, Inc., 1983.

End of Construction Season (Year)	Net Cash Flow with Projects per Season		
	8	10	12
0	$-100,000	$-100,000	$-100,000
1	$ 24,000	$ 30,000	$ 36,000
2	$ 24,000	$ 30,000	$ 36,000
3	$ 24,000	$ 30,000	$ 36,000
4	$ 24,000	$ 30,000	$ 36,000
5	$ 24,000	$ 30,000	$ 36,000

Table 6: Annual Net Cash Flows For The Form Cleaning Robot Investment.

Projects per Season	Net Present Value (NPV) with MARR =		
	5%	10%	15%
8	$ 2,500	$-10,000	$-21,000
10	29,000	12,500	- 1,000
12	54,000	34,500	19,000

Table 7: Net Present Values of Form Cleaning Robotization Projects.

11 Sensitivity Analysis

Initial simplified sensitivity analysis of project parameters has already been performed with respect to the Minimum Attractive Rate of Return (MARR) and the number of projects performed during each construction season. There are numerous ways to test the sensitivity of the form cleaning robotization project feasibility with respect to project's relevant parameters. The number of these parameters is large, and an exhaustive sensitivity analysis with respect to all of them is beyond scope of this paper.

The parameters of the sensitivity analysis to be addressed include the following:

1. The Minimum Attractive Rate of Return on the project.

2. Number of construction projects on which the robot is to be used per construction season.

3. Number of construction seasons in which the robot is utilized.

4. The cost of manual and technical/professional labor.

5. The initial investment in robot.

6. Level of improvement in work quality due to implementation of robot.

7. Other miscellaneous factors (rate of technical progress in robot technology and in the construction work, demand for construction activities, supply of labor, etc.).

As an example, sensitivity analysis of the robotization project has been performed on the given data with respect to the cost of manual labor employed on the construction site. It was assumed that the labor cost increased by 10 percent, and the impact of such an increase on selected project parameters was examined.[14]

11.1 "Break-Even" Initial Robot Investment Cost

As an another example, "break-even" cost of a contractor's investment in a robot occurs when the *Net Present Value* of the robot-performed work equals zero. These costs of the form cleaning robot calculated for three values of MARR and for three values of the number of projects performed per season are contained in table 8.

MARR	Projects per Season		
	8	10	12
5%	$104,000	$130,000	$156,000
10%	91,000	114,000	136,000
15%	81,000	101,000	121,000

Table 8: "Break-Even" Costs of Form Cleaning Robot to Contractor Under Varying Conditions.

[14]Detailed results of this analysis are not included in this paper.

12 Conclusions

It was confirmed that the implementation of robotic equipment to construction and construction-related work tasks makes engineering sense only with operations that are extremely simple and repetitive for human unskilled workers, and economic sense only if the quantity of work is large enough to justify the investment in an always yet expensive robotic equipment. The negative Net Present Values of robotization projects under the assumed Minimum Attractive Rates of Return and for the given number of projects per season indicate that the implementation of robot under such circumstances is economically infeasible. Where the NPV value for a project is positive, then such a project should be given the contracting firm management's attention.

Our preliminary analysis of the form cleaning robot suggests that under a high enough robot utilization level its application on the construction site may prove economically feasible and therefore attractive to U.S. construction firms. Similar analysis for other comparable applications of construction robot may also reveal satisfactory results.

The case study of a form cleaning robot presented above should also be analyzed within other dimensions of the analysis framework. For example, the impact of time on anticipated costs of individual robotic components and their influence on the robotic work process in question must be addressed. Concurrently, a comparison of costs and benefits of proximate vs. in-warehouse roboticized cleaning of concrete forms can be performed.