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Construction Robot Implementation Logistics

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Abstract

Robotics implementation on construction sites poses significant challenges to both contractor firm management as well as technical staff. Only a few large construction firms in Japan currently utilize fleets of robotics in diverse work tasks. Similar equipment is expected to be implemented by large construction firms in other industrialized nations. However, for a number of years in the near future, the robots will be regarded by these organizations as scarce resources which must be managed wisely in order to produce satisfactory technical and economic benefits for their users. This paper addresses significant robot implementation logistics problems associated with optimal robot assignments to diverse construction tasks and sites operated by a user contractor firm. Decision support architecture for the performance of robot assignment plans is described. This architecture includes both algorithmic and expert system methodology in the formulation of robot implementation criteria and goals. Implications of the presented approach to robot implementation logistics are presented within the framework of a *Construction Robotic Equipment Management System (CREMS)* currently under development at Purdue University for the Ohbayashi Corporation .

Introduction

Although construction robotic fleets are not yet a commonplace in a vast majority of construction organizations throughout the world, most of the largest contracting firms in Japan have developed a number of working robot prototypes. These prototypes, in most cases, are currently undergoing further technical refinements to better suit the needs of varying jobsites at which they are expected to perform their work tasks.

Construction robot research and development resulted in large amounts of resources committed by the firms which undertook such efforts. One of the most important implied assumptions made in R&D investment decision making was one of future economic payoff on each such robot investment. The economic payoff can be achieved only if robot implementation decisions are made on a sound engineering basis. As an aid in such decisions, *Construction Robotic Equipment Management System* (CREMS) is currently under development at Purdue University (Skibniewski 1989a, Skibniewski 1989b, Russell 1990, Skibniewski 1990). CREMS analyzes the match between construction job tasks as required on specific projects sites and the capabilities of robots in disposal by the Ohbayashi Corporation, one of the leading Japanese international construction, engineering and development firms. Four basic modules constitute the CREMS architecture: CTAM (Construction Task Analysis Module), RCAM (Robot Capability Analysis Module), REEM (Robot Economic Evaluation Module) and RILM (Robot Implementation Logistics Module) (see Figure 1). This paper describes the research concepts focusing on the development of RILM.

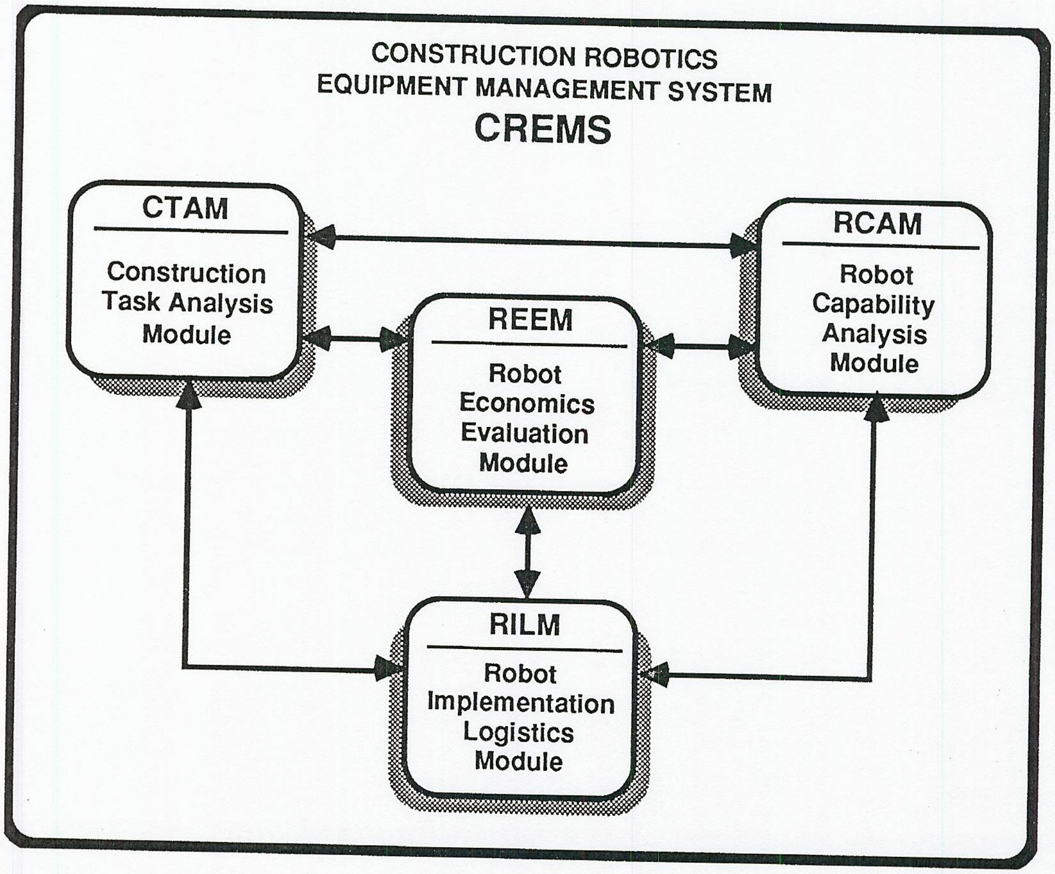


Figure 1. The Principal Modules of CREMS.

Implementation Logistics Issues

Once the suitability of a given robot for the performance of a specific construction task is determined, the robot can be assigned to that task and dispatched. However, as it is frequently the case with a large construction company, more than one project site will compete for the robot assignment at any given time. Thus, considering the robots as scarce resources, sound and timely dispatching decisions must be made based on a careful weighing of each assignment's advantages and disadvantages. The variety of decision issues is quite complex and includes task work volumes, task durations and sequences, job site locations and associated travel distances, robot setup, operation and dismantling resources needed, and others.

The basic methodology of robot assignment to construction tasks can also be applied to the assignment of other, more conventional types of construction equipment treated as scarce resources by contractors, such as tower cranes, excavators, small material handling equipment, and other.

Dynamic linear programming assignment modeling involves an establishment of a robot implementation cost function, subject to assignment constraints representing the fact that any given robot can be assigned to only one project site at a given time. In general, the linear programming assignment model suitable for making robot assignment decisions can be represented in the following form:

minimize:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij}$$

subject to:

$$\sum_{i=1}^{m} x_{ij} \leq 1 \qquad i=1,2,...,m \quad \text{(robots)}$$

$$\sum_{j=1}^{n} x_{ij} \leq 1 \qquad j=1,2,...,n \quad \text{(project sites)}$$

$$x_{ij} = 0 \text{ or } 1$$

In this model cost coefficients c_{ij} represent a composite cost of assigning robot "i" to project site "j". The main difficulty lies in the fact that these assignment costs are dynamic in nature and depend primarily on the current location and duration of task which the robot is performing. Also, attempts to apply classical stochastic Markovian job scheduling models to the representation of this model are very difficult due to limited availability of relevant performance data.

The complexity of the robot assignment problem precludes the use of one purely classical methodology such as a dynamic linear programming assignment model in the assignment decision making. A hybrid decision model containing both classical optimization approaches and heuristic knowledge is necessary. Such a model can encompass the specific challenges facing construction equipment managers when dealing with relatively new and unfamiliar equipment.

Research on robot implementation logistics leads inevitably to the necessity of creating a suitable heuristic knowledge base to work in tandem with an algorithmically structured assignment process. First, traditional project scheduling tools seem highly applicable and relevant to the robot assignment issue. In particular, the Critical Path Method (CPM) combines the information on project task duration and task precedence relationships. These relationships result in the determination of critical activities and projects as well as allowable slack times available for optional activity. Second, heuristics approach to scheduling offers the advantage of utilizing the experience of skilled robot and conventional construction equipment managers in making assignment decisions.

Combining the two approaches requires the fulfillment of the objective of maximizing the contractor's profit resulting from the utilization of robots in regard to all projects currently in the firm's portfolio. This implies that, in making an assignment decision, the robot dispatcher must take into account the net benefit of utilizing robot across all projects at the same time, if feasible. Thus, project activity shifting may be required to accommodate limited robot availability even at the cost of either crashing an activity performance time or delaying overall project completion, as long as the net profit to the firm will be positive when compared with the option of performing the tasks without the use of robots.

Robot Implementation Logistics Architecture

The implementation logistics issues presented above have been compiled into a coherent structure allowing for input of specific project information as well as information regarding robot specifications and performance characteristics. The process labeling format follows the general format used in the development of *Construction Robotic Equipment Management System* (CREMS). Thus, the processes involved in the *Robot Implementation Logistics Module* (RILM) are labelled PRO-13 through PRO-16 (see Figure 2). Several procedures are included in the robot assignment process, as specified below.

Procedure 1: Compile List of Projects and Establish Logistic Parameters

This procedure utilizes input from the previously developed *Robot Economic Evaluation Module* (REEM) as part of the entire CREMS program (see Figure 1). REEM evaluates the robot versus non-robot task performance cost and produces the following information: 1) generic non-robot work performance cost; 2) generic robot work performance with supplementary non-robot task cost; and 3) the robot implementation decision.

Based on the information provided by REEM, PRO-13 in RILM compiles a listing of all projects sites which have economically justified the use of the robot. Prior to being included on the list of projects considered for robot implementation by RILM, all projects and their associated tasks must have been screened previously by the cost feasibility analysis procedure of REEM.

PRO-14 establishes constraints and parameters for the logistic scheduling. The following parameters are being identified: project characteristics, "task_project" characteristics, maintenance, and transportation (see Figure 3). The data compiled for the considered construction projects are stored in a computer file in order to dynamically access it for the subsequent preliminary scheduling of robot activities and project resource leveling at PRO-15 and PRO-16, respectively.

Procedure 2: Preliminary Scheduling for Robot Implementation Logistics

PRO-15 performs preliminary scheduling by means of two types of scheduling charts: 1) a Gantt chart defining the precedence relationships of the projects listed in PRO-13, and 2) a down-hill chart which provides input to PRO-16 (resource leveling).

The project Gantt chart includes the earliest and latest start as well as finish times for each project, the sequence of activities in a project (a unit scheduling activity regarded as project component such as one concrete floor to be finished in a multistory building is called a "task_project"), available crash times, and the preference order between the listed projects (P(i) is the ranking of the preference order of the i^{th} project). An example of project data is shown in Figure 6. The robot application preference order is determined by the preference rules as shown in Table 1. When a decision maker wants to decide the ranking of the projects illustrated in the Gantt chart, he can choose one or more particular preference rules from Table 1.

The project Gantt chart is transformed into a project down-hill chart according to the preference ranking of each project, through the earliest or latest start time. Figure 7 shows an example of the project down-hill chart obtained through the use of the earliest start time. When scheduling robot implementation, the lowest phase is designated as the critical phase in this Figure. Only "task_projects" associated with the critical phase are performed by the robot, while "task_projects" in other phases employ non-robot work. Scheduling for the critical phase, which has characteristics similar to the critical path in CPM, plays an important role in the next procedure PRO-16 (resource leveling).

Procedure 3: Resource Leveling for Robot Implementation Logistics

The algorithm for the resource leveling procedure PRO-16 is shown in Figures 4a and 4b.

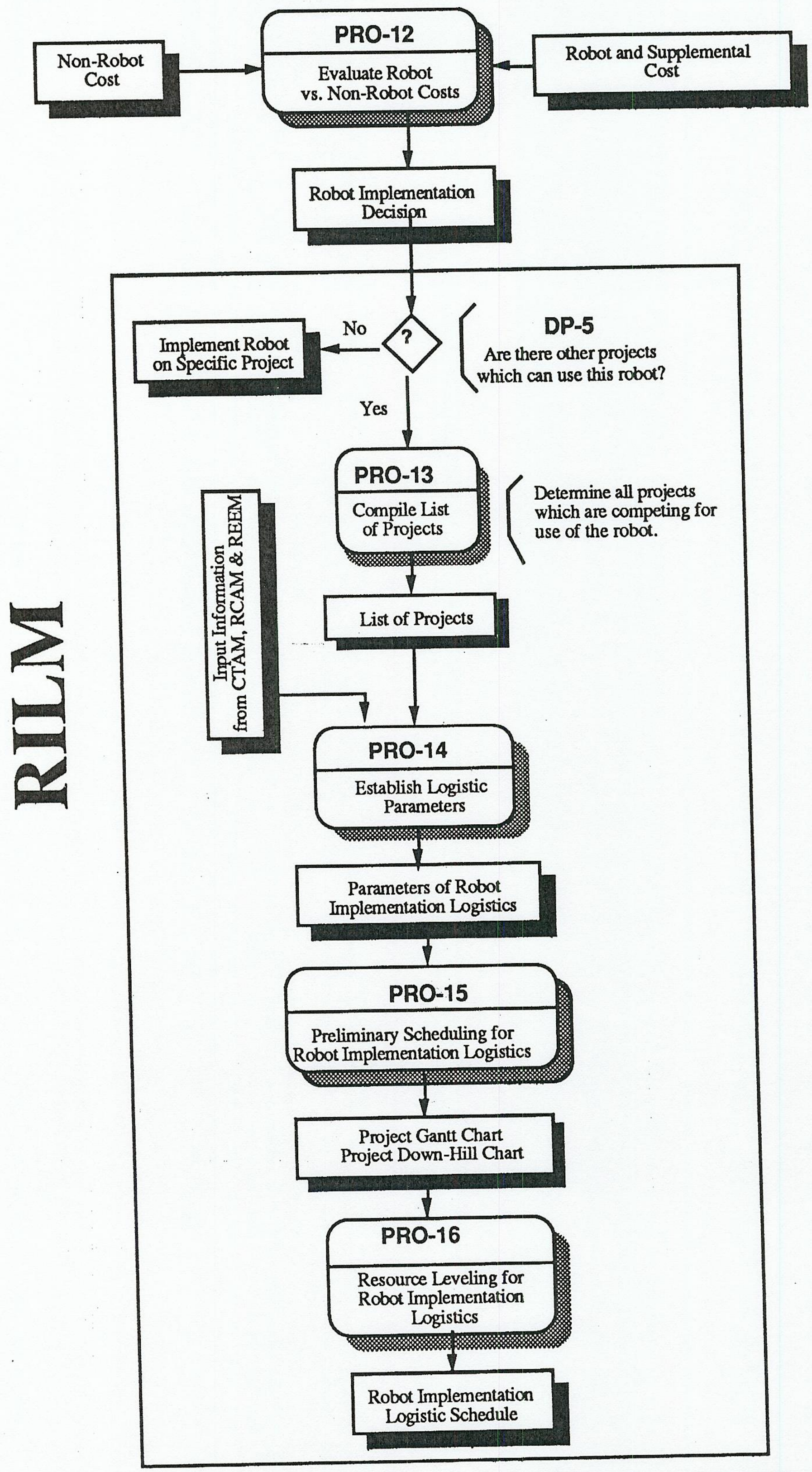
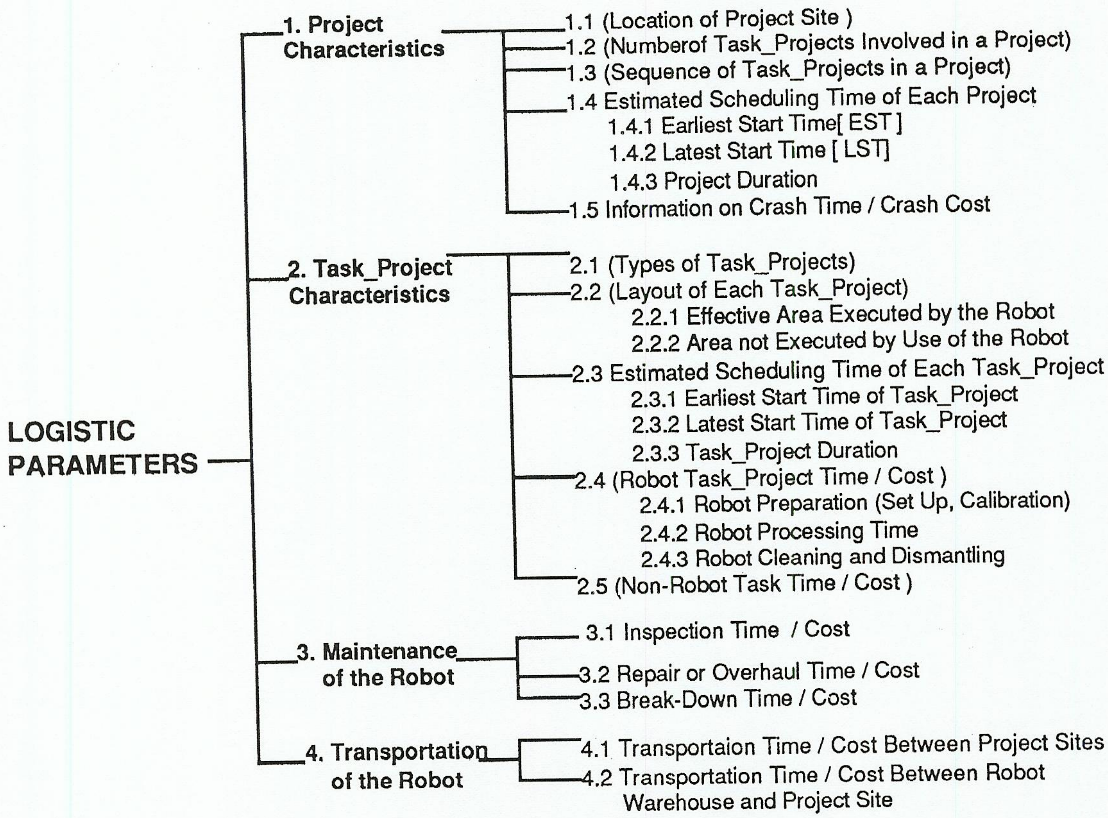


Figure 2. Conceptual Framework of RILM within CREMS.



Note: Parameters in parentheses denote input parameters from CTAM, RCAM and REEM.

Figure 3. Parameters in Robot Implementation Logistics.

Preference Rule No. (1)	Preference Criterion (2)	Example Rule (3)
PR1	Robot Work Profit (RWP) in Comparison with Non-Robot Work: $RWP = \frac{\text{(Non-Robot Cost) - (Robot Cost Plus Supplementary Cost)}}{\text{Number of Task\_Projects Involved in a Project}}$	if RWP ≤ ¥ 100,000 per project then do not use robot
PR2	Number of Robotable "Task_Projects" Involved in a Project	if number of "task_projects"< 3 then do not use robot
PR3	Total Project Duration	if total project duration ≥ 3 months then consider sharing robot with other projects simultaneously
PR4	$\text{Robot Effectiveness} = \frac{\text{(Total Area)-(Area Not Executed by Robot)}}{\text{Total Area}}$	if robot effectiveness ≤ 70% then give preference to another "task_project"

Table 1. Example Preference Criteria and Rules for Basic Robot Scheduling.

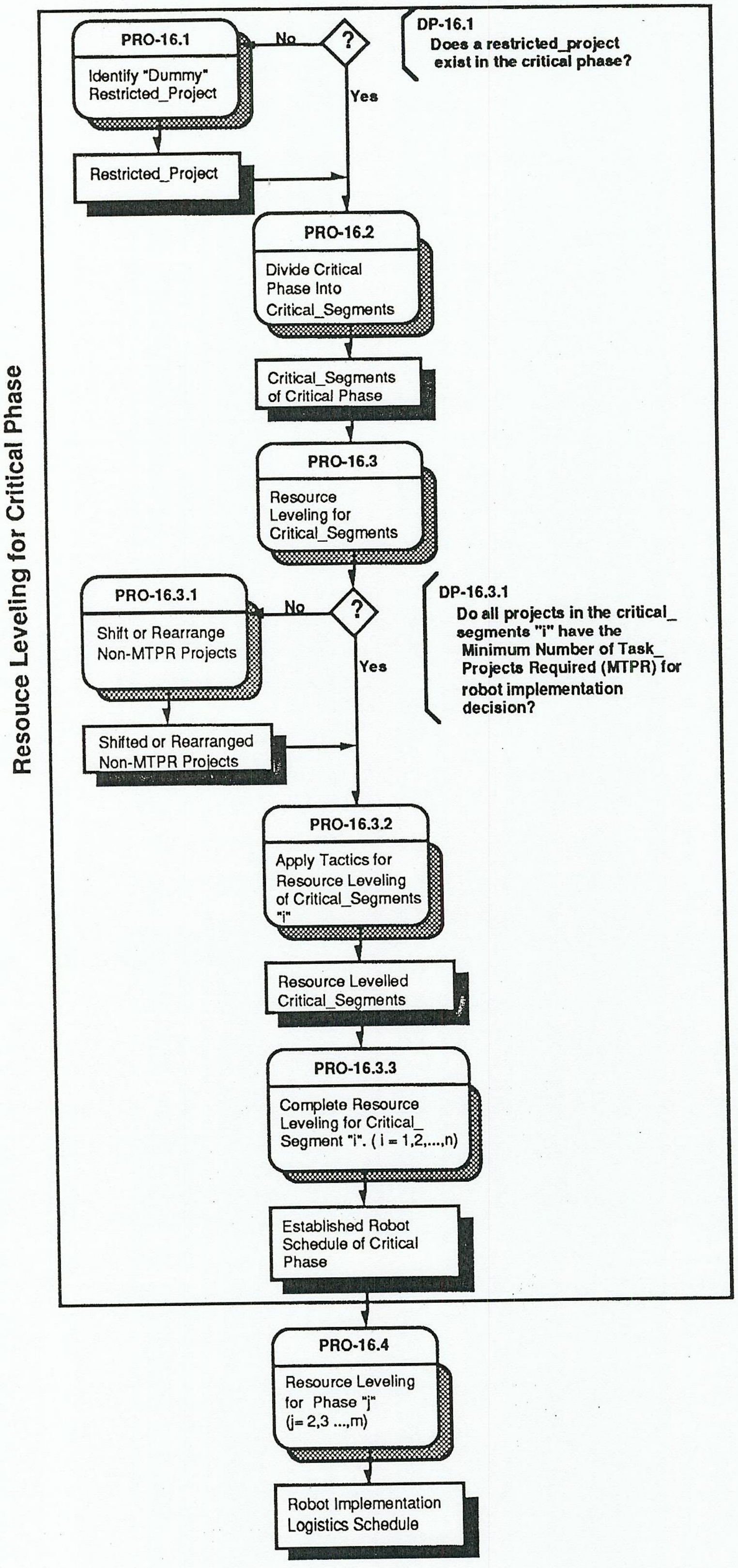


Figure 4a. Strategy of Resource for Robot Implementation Logistics (PRO-16).

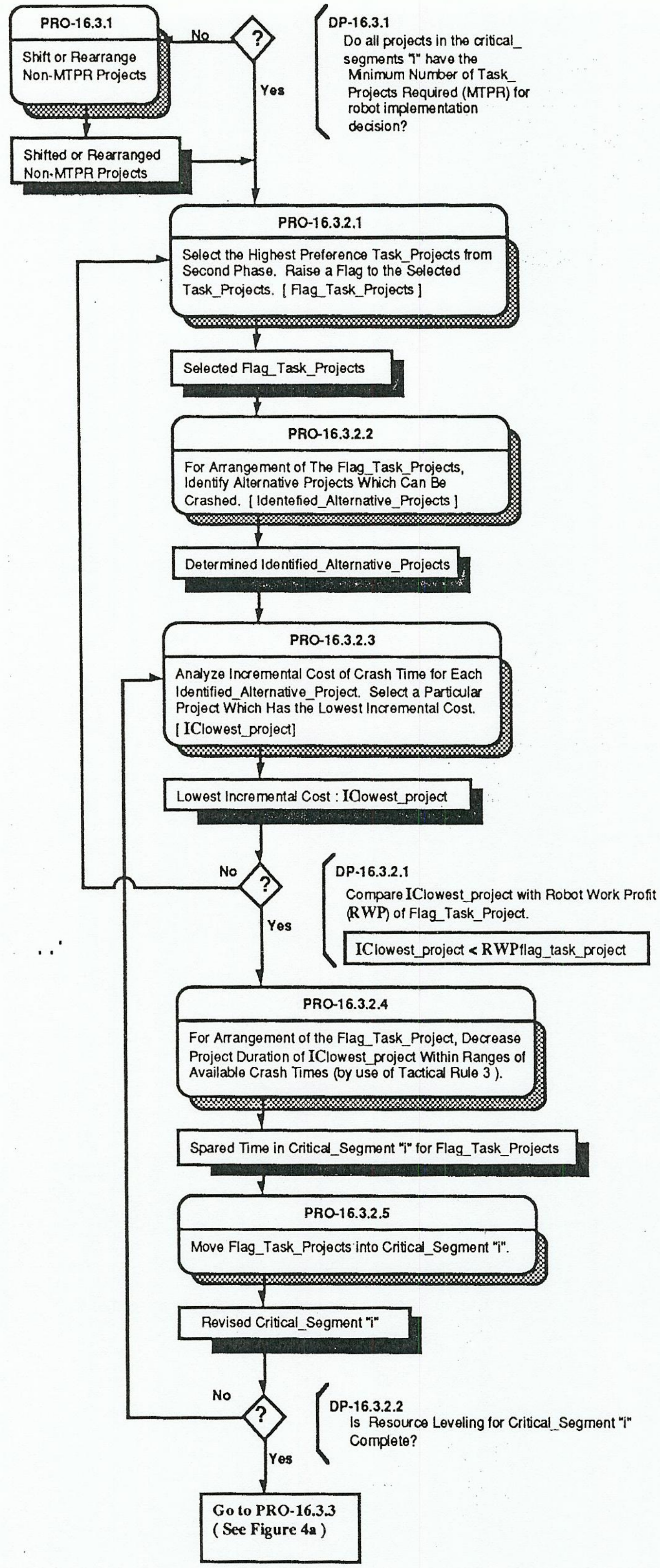


Figure 4b. Expansion of Tactics for Resource Leveling for Critical Segment "i" (PRO-16.3.2).

The main objectives of this procedure are: 1) minimizing the idle time of the robot in relation to the critical phase schedule, 2) leveling the use of labor crafts associated with the other phases, and 3) reducing the total costs of logistic scheduling for the whole project duration. Meeting these objectives, "task_projects" shifting or rearranging in the project down-hill chart lead to reduced period-to-period fluctuations in resource requirements.

Figure 5 illustrates the rule structure as a hierarchical classification of the resource leveling problem, and tactical rules as heuristic scheduling rules used to determine how to shift and rearrange competing "task_projects."

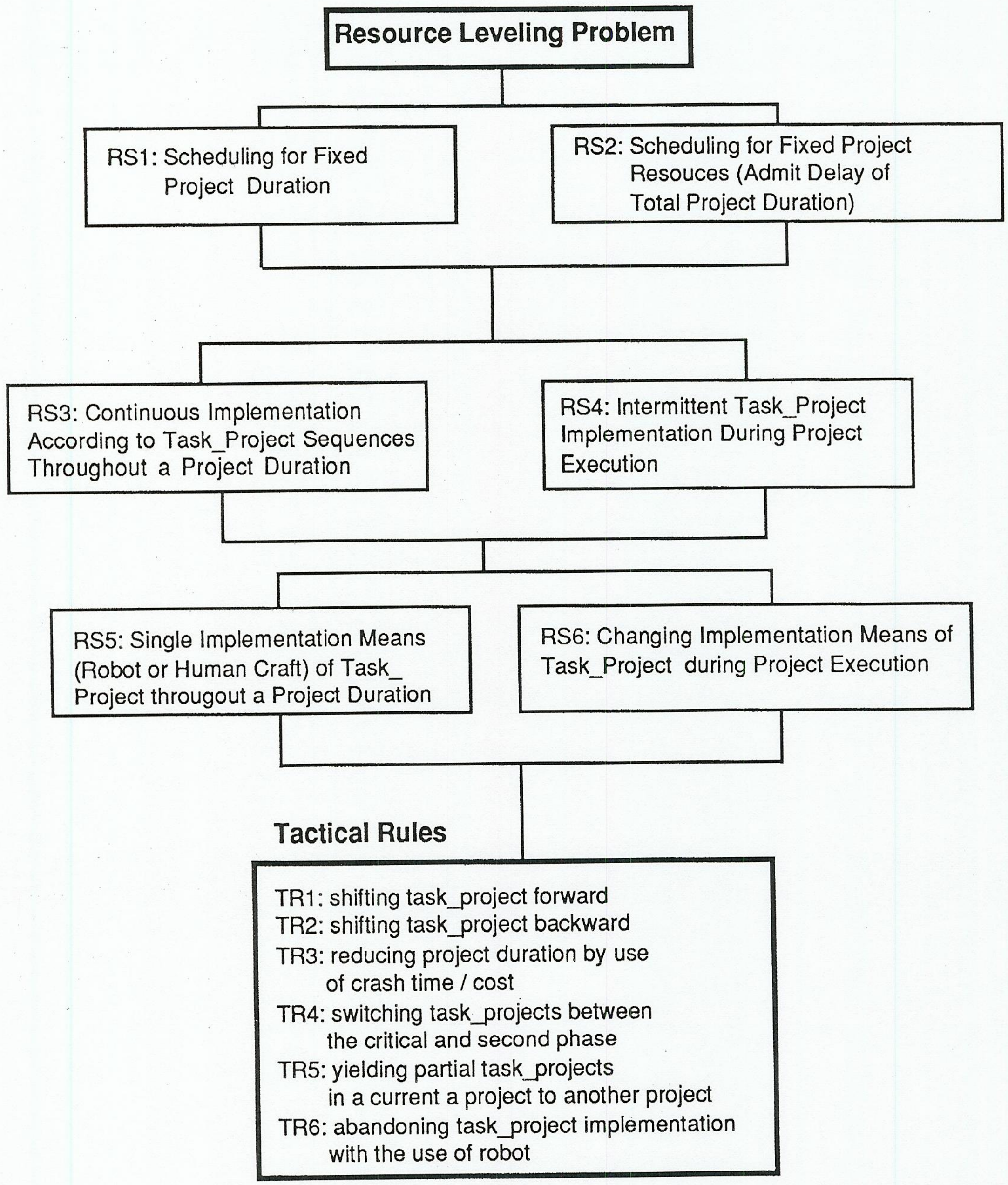


Figure 5. Rule Structure (RS) and Tactical Rules (TR) in Resource Leveling.

The algorithm presented in Figures 4a and 4b is intended to aid a decision maker in a systematic solution to the complicated resource leveling problem with the use of an interactive computer procedure. The algorithm is applied to a case shown in Figure 8. To begin with the resource leveling, the decision maker must consider the critical phase concerned with the robot scheduling.

Before describing each process in the algorithm, two terms are defined. First, projects in which the earliest start time is equal to the latest, (i.e., with no "total float time"), are designated as "fixed_projects." Second, a "fixed_project" which is in the critical phase is called a "restricted_project." Since a "restricted_project" possesses high preference and the fixed start point of the project duration, it may force the decision maker to adjust the competing "task_project" schedules associated with the predecessor or successor projects against its own constrains. Therefore, the clarification of where the "restricted_project" is located in the critical phase is a prerequisite for resource leveling in the other remaining projects. This step is implemented at a decision point labelled DP-16.1. Project "E" is a "restricted_project" (Figure 7). If there are no "restricted_projects" in the critical phase, the decision maker must decide tentatively on one particular project of his choice among the high preference projects (PRO-16.1). Subsequently, PRO-16.2 divides the critical phase into several segments according to the determined position of the "restricted_project." The divided segments are designated as "critical_segments."

PRO-16.3 is a process of resource leveling for the "critical_segment" "i" (i=1,2,..n). Decision point DP-16.3.1 identifies a project without a "Minimum Number of 'Task_Projects' Required for Robot Implementation Decision" (MTPR) in the "critical_ segment" "i." The MTPR is a marginal number of "task_projects" which ensures the effective implementation of the robot work. MTPR should be calculated through the analysis of a profit/loss break-even point between the robot and human craft work, or can be obtained from prior robot implementation experience.

One function of PRO-16 involves handling of projects in which the expected robot work is insufficient to guarantee its economic attractiveness (PRO-16.3.2). In cases where a project not involving the MTPR (non-MTPR project) exists in the segment, its predecessor or successor project is shifted or rearranged by means of the tactical rules 1 through 6 shown in Figure 5.

In order to improve the robot operationability, after processing a non-MTPR project, PRO-16.3.2 focuses on further increasing the number of "task_projects" in the "critical_segment" i by utilizing the available float times and crash times of project duration (Tactical Rules 1 through 3).

Resource leveling for the critical phase is currently complete. In the same way as resource leveling for other "critical_segments" (e.g., see Figure 7), the effective scheduling method for noncritical phases j (j =2,..,m) against the critical phase is based on man-power leveling with available float times. This is usually preferred to reducing project duration obtained through applying activity crash schedules, because the upper (noncritical) phases do not require strict adherence to their original schedules established before the robot employment had been considered.

Example Application of RILM Procedure

The application of RILM scheduling methodology is illustrated on eight example projects involving finishing cast-in-place concrete (refer again to Figure 6). The concrete surface finishing robot and available for implementation within these projects is the Automatic

Laser Beam-Guided Floor Robot from the fleet owned and operated by the Ohbayashi Corporation of Japan.

Each project in Figure 6 includes the following information:"task_project" code, earliest and latest start time, project duration, preference ranking order, and available activity crash times. The preference order is determined here in view of preference rule No. 2 regarding the number of "task_projects" involved in a given project (Table 1). Figure 7 is a result of the preliminary scheduling process described earlier in the paper. Assuming that in this case MTPR includes less than three "task_projects", projects "G" and "H" are regarded as non-MTPR projects. In resource leveling for "critical_segment" 1, project "B" should have a priority for schedule adjustment because of its higher preference ranking. Depending on decision point DP 16.3.2.1 (refer again to Figure 4b), project "B" has a crash time, and the incremental cost for the crash time is less than the RWP (see Preference Rule 1: Robot Work Profit in Comparison with Non-Robot Work, Table 1). Therefore, the duration of project "B" is shortened and the "task_project" "B-1" is moved into the critical phase (Figure 4b: PRO-16.3.2.4, and Tactical Rule 3). Applying the algorithm in Figures 4a and 4b, as well as the Tactical Rules in Figure 5, an example result of the resource leveling is obtained as presented in Figure 8.

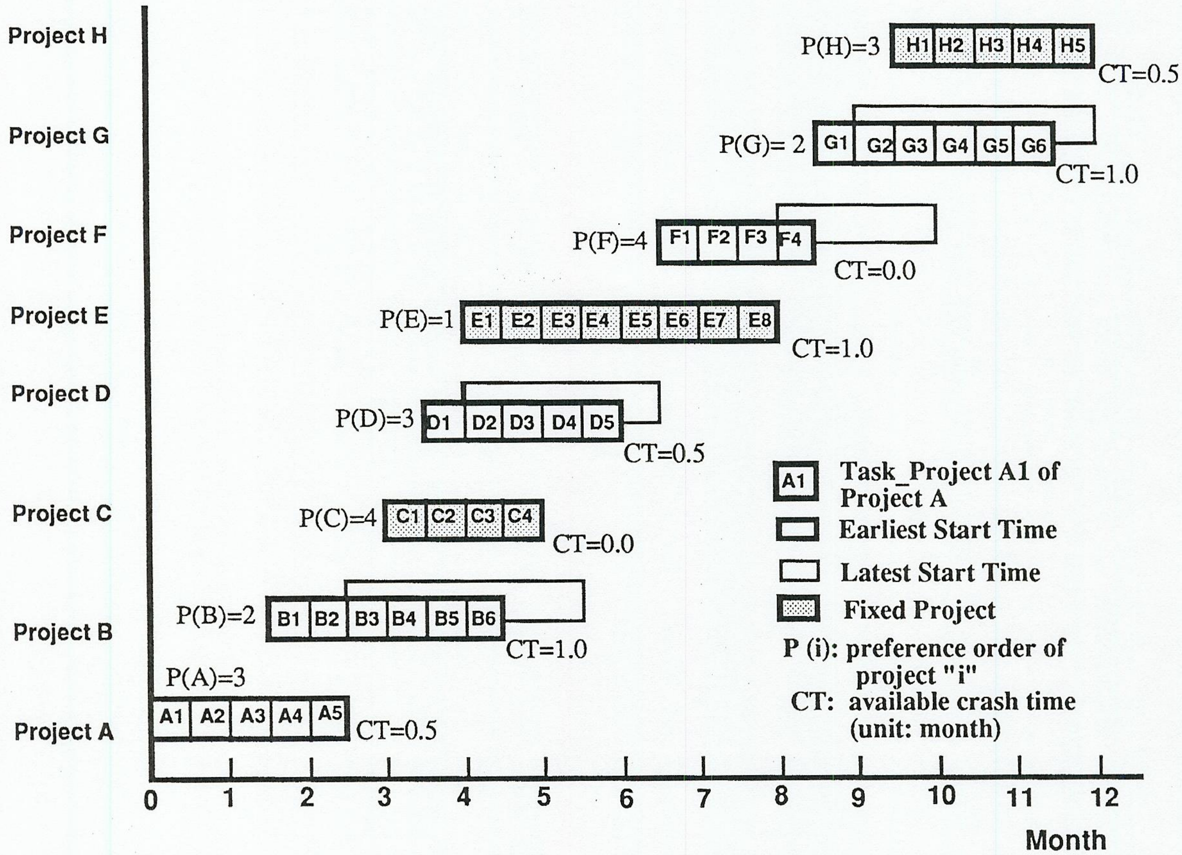


Figure 6. Project Gantt Chart for Preliminary Scheduling.

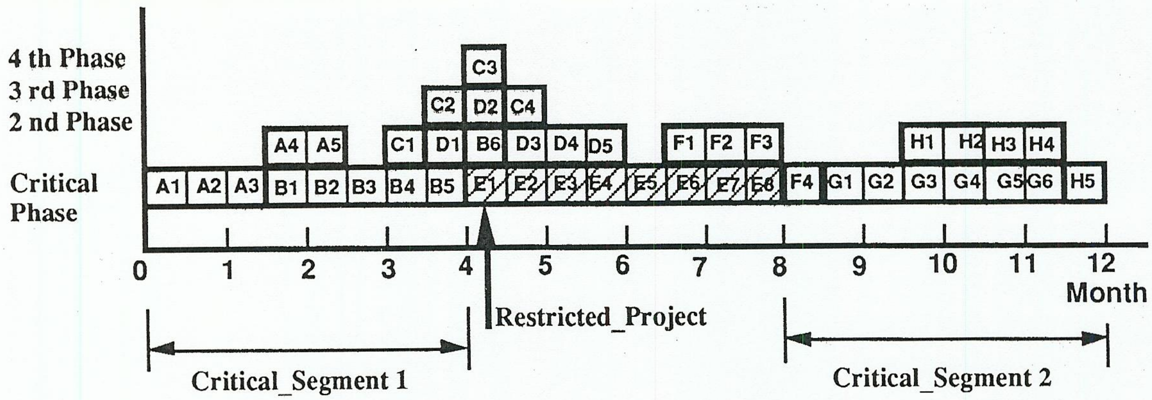


Figure 7. Project Down-Hill Chart for Preliminary Scheduling.

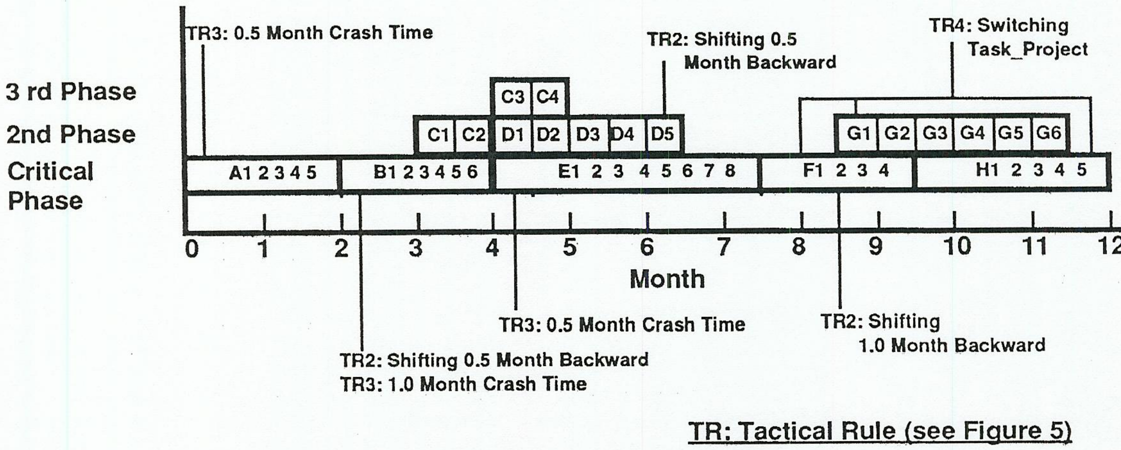


Figure 8. Result of Resource Leveling.

Conclusions

Robotics application logistics is a complex issue that requires substantial research and development. Several relevant development tools have been identified, including mathematical modeling, traditional CPM/PERT and related schemes, and expert system based methodologies. Practical integration of these tools into a useful decision support system is necessary.

Current research efforts focus on the prototyping and development of the Robot Implementation Logistics Module (RILM) of the Construction Robotic Equipment Management System (CREMS) within the Hypercard™ programming environment (Skibniewski 1990). Subsequently, the field experience with the Ohbayashi Corporation robotics will be incorporated into the prototype for use with future construction projects.

Acknowledgments

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