AN EXPERT SYSTEM FOR PLANNING IN ROBOTIZED CONSTRUCTION

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1. Introduction

The robotization of building construction is expected to represent a breakthrough in terms of construction productivity, improvements in safety and quality and the speed-up of the work itself.

On the other hand, there have been some concerns over the ability of managers to oversee robot-related work in the construction process, based on their experience and subjective judgement with traditional construction management techniques. Managers may, consequently, fear low productivity from robots and delay work at the site, a problem which might directly affect the cost and duration of the construction project.

In this paper, the author discusses the methodology to implement the expert systems which will be used to generate construction plans suitable for the constraints and conditions of robotized construction. The author developed his model for construction process at the site, which was then used to serve as a data structure for ill-structured knowledge of construction plans and schedulings. The model described here is named "Process Graph". It was developed for system simulation of the construction process[1). The following offers some typical rules and their logics of inferences based on this model, which will be discussed to demonstrate the capability of the methodology.

2. Planning for Robotized Construction

2.1. Needs for Expert System

To evaluate a plan for robotized construction, the cost and time might be essential criteria to gauge the propriety of the plan, while quility and safety should be regarded as necessary conditions required in specifications, drawings, codes and regulations.

In traditional building construction, labor costs are estimated at approximately one-fourth to one-third of total construction costs. Therefore, it is very important for construction managers to implement proper planning and scheduling in order to raise the productivity of both robots and labors at the site.

A project's duration is one of the most essential criteria for clients to evaluate the capability of construction managers, because any delays will naturally mean a setback of any opportunity to complete the building earlier than competing bidders. Apart from the productivity of robots and labors, the duration depends on proper activity priorities and resource allocations.

To rationalize robotized construction work, construction managers need an expert system for planning which can take into account all information required to optimize the plan.

2.2. Concept of the Expert System

The expert system for construction planning should generate a construction plan suitable for a specific construction project. The project is defined by specifications, drawings, site conditions and other constraints. To generate a usable construction plan, the expert system should have the ability to carry out forward chaining inference mechanisms, and also should apply the knowledge bases according to construction planning procedures and to construction method.

The expert system is represented in Figure 2.1. The system consists of four subsystems. The Planning Board is the working memory which stores the construction plan during the inference process. At the beginning of inference operations, the working memory contains only the information of specifications, drawings, site conditions and other constraints, and after inferences this information are developed into the final construction plan.

The knowledge base on construction planning procedure is the database which sends instructions to the inference engine on how to develop a good plan, which sub-plan to proceed with next, and so on.

The knowledge base on construction method is the database which supplies the inference engine with construction engineering information, such as the work packages to be required, conditions to start activities, and relationships between activities.

The inference engine works as a management leader in a supervisory role to assist each construction manager in developing the construction plan.

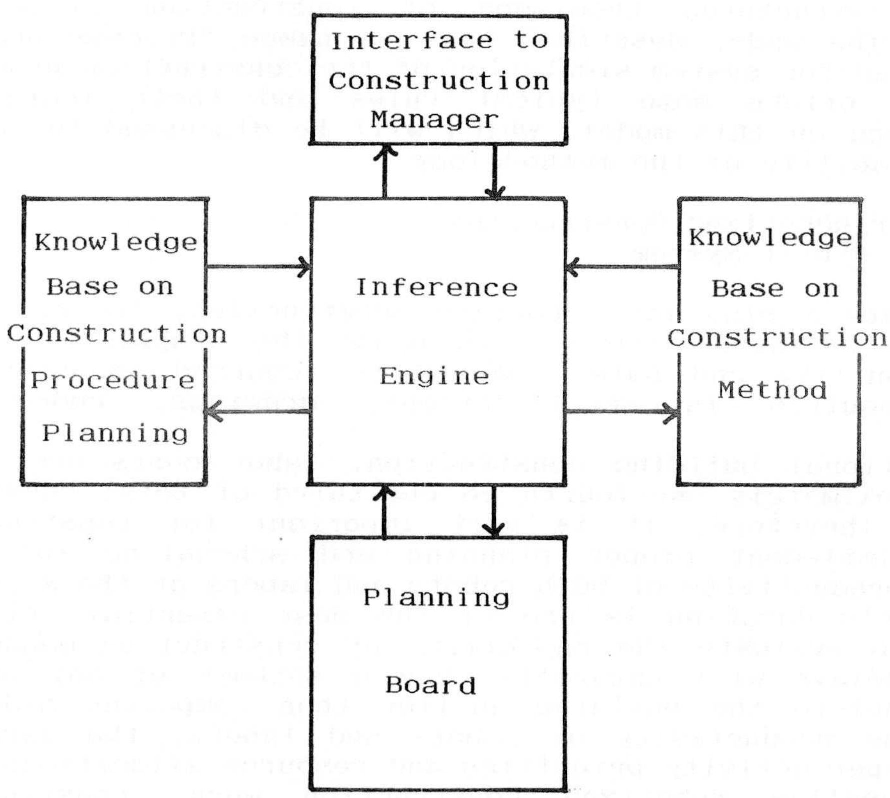


Figure 2.1 Expert System for Construction Planning

3. Model of Robotized Construction Process

3.1. Representation by Process Graph

A Process Graph was developed originally as a modeling tool for system simulation of the construction process. This graph has several advantages to model the construction process, one of which is the capability to show explicitly the relationships among events which will occur at the construction site.

The ability of the Process Graph to represent the construction process is essential to develop an expert system which stores not only the knowledge required to generate the construction plan, but also various alternatives for the plan as it is generated.

Figure 3.1 illustrates a simple example of the Process Graph, where each node represents the information on the event at the site. An arrow is used to define the relationship between two events. For instance, an arrow between node S1 and node A1 defines that Activity (A1) is performed in Space (S1). An arrow between node R1 and node A1 defines that Resource (R1) is used in Activity (A1). An arrow between node A1 and node E1 defines that Activity (A1) produces Building element (E1).

The underlined portions of the above paragraph indicate the definition of an arrow. This characteristics that English-like rules (or Japanese-like rules) can be easily transformed into an arrow notation is well adapted for building the knowledge base required for construction planning.

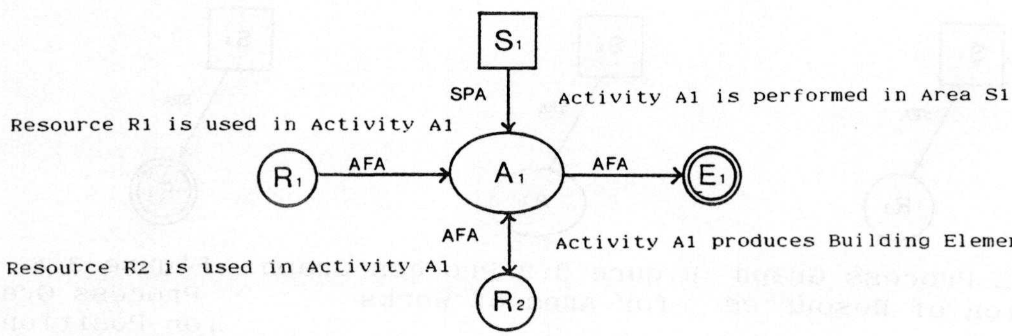


Figure 3.1 A Simple Example of Process Graph

To apply the notations in the Process Graph for the expert system, some parts are modified and exanded. The Advanced Process Graph consists of the following six nodes and eleven arrows. The type of arrows, however, will be added according to the expansion of the capability.

< node >

1. Resource Node : Robot, Labor, Material, Equipment
2. Activity Node : Assembly work, Transportation work
3. Element Node : Column, Beam, Wall, Fixture
4. Space Node : Work space, Stockyard, Floor
5. Condition Node : Condition, Constraint
6. Function Node : Probability, Loop

< arrow >

1. Space Arrow : Activity (A0) is performed in the Space (S0)
2. Transport Arrow : Activity (A0) transports Resource (R0)
3. Catalyst Arrow : Activity (A0) uses Resource (R0)
4. Active Factor Arrow : Activity (A0) prodeces Building Element (E0)
5. Object Arrow : Activity (A0) repairs Resource (R0)
6. Precedence Arrow : Activity (A0) precedes Activity (A1)
7. Control Arrow : Activity (A0) controls the finish time of Activity (A1)
8. Condition Arrow : Activity (A0) activates Condition (C0)
9. Adjacent Arrow : Space (S0) is adjacent to Space (S1)
10. Is-a Arrow : Activity (A0) is one of Activity (A1)
11. Consist-of Arrow : Activity (A0) consists of Activity (A1)

3.2. Notations of Advanced Process Graph

3.2.1. Location in the Site

To indicate the location with a graph notation, a Space Arrow (SPA) is used in connecting Space Node to Resource Node, Activity Node and Element Node.

Figure 3.2 shows that the resource (R1) is stored at the stockyard (S1). Figure 3.3 shows that the activity (A1) is performed in the area (S2). Figure 3.4 shows that the building element (E1) will be fixed on the location (S3).

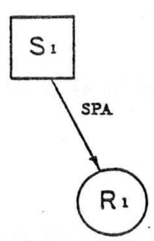


Figure 3.2 Process Graph for Location of Resources

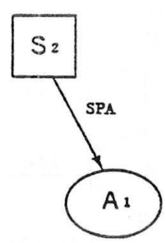


Figure 3.3 Process Graph for Area of Works

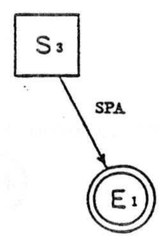


Figure 3.4 Process Graph for Position of Building Elements

3.2.2. Work Package

Activities in the construction process have been classified into the following three types of work.

1. Transport Work : Horizontal transportation, lifting, etc.
2. Assembly and Disassembly work : Fixing, Bending, Cutting, Dismantling, etc.
3. Miscellaneous work : Inspection, Curing, Storing, etc.

To represent a transport work of resource, two Transport Arrows (TRA) are used connecting the Activity Node and the two Resource Nodes, which indicate two resources before transport and after transport.

Figure 3.5 shows the work (A3) where the resource (R4) in stockyard (S5) will be transported to another stockyard (S6).

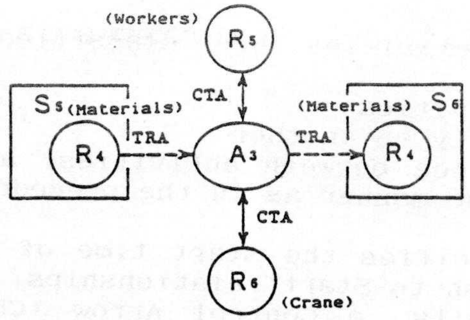


Figure 3.5 Process Graph for Transport Work

To represent assembly and disassembly work, Active Factor Arrow (AFA) are used for connecting the Activity Node to the Resource Node (or Element Node).

Figure 3.6 shows the assembly work where workers (R7) assemble the materials (R8 and R9) to produce the building element (E3). Figure 3.7 shows the disassembly work where workers (R10) use a crane (R11) to disjoint scaffoldings (R12) into tubular-steel scaffolds (R13), braces (R14) and platforms (R15).

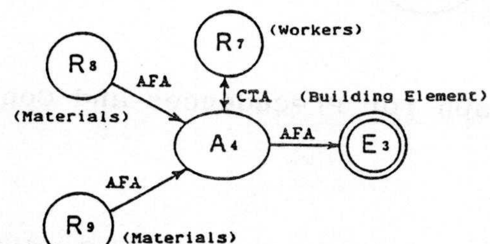


Figure 3.6 Process Graph for an Assembly Work

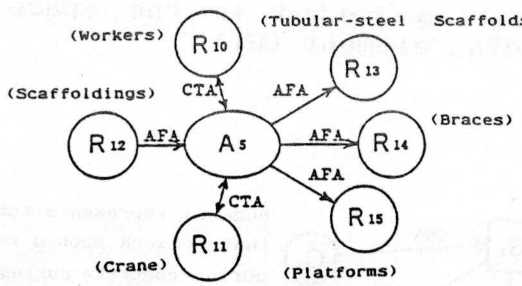


Figure 3.7 Process Graph for a Disassembly Work

To represent such miscellaneous work as inspection and storing, Object Arrows (OJA) are used for connecting the Activity Node to the Resource Node. An Object Arrow means that there is no significant change in the resource (or building elements) after these works have been performed.

3.2.3. Sequence of Activities

Relationships between activities are classified into the following two types:

1. Precedences between activities
2. Controls from one activity to another

To represent the precedence between activities, a Precedence Arrow (PRA) is used in the same manner as in the precedence network diagram.

The Precedence Arrow specifies the start time of an activity using Start-to-Start and Finish-to-Start relationships. To control the finish time of an activity, a Control Arrow (CLA) is used to represent the logic that one activity's start or finish will interrupt the other activity. Figure 3.8 shows the process where the work (A7) of setting a ceiling panel requires the work (A8) of holding the panel at the same time, and when the work of nailing (A9) is completed, such work (A8) will be unnecessary.

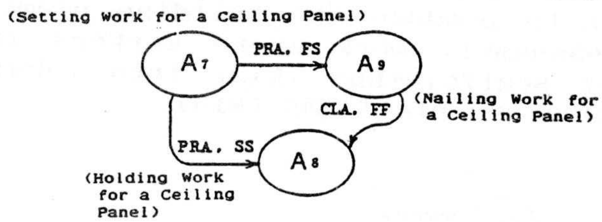


Figure 3.8 Process Graph for Precedences and Controls

3.2.4. Conditions

A set consisting of Condition Node and Condition Arrow is used for representing the occurrence and expiration of a specific condition in the site. For instance, congestion in a work space is caused by stored materials. After an activity is completed, the condition of the work space may have undergone change. Figure 3.9 illustrates how the activity (A1) produces the building element (E1), which will make the condition that no work should be performed during concrete curing period in the space (S1) due to the placement of the building element (E1).

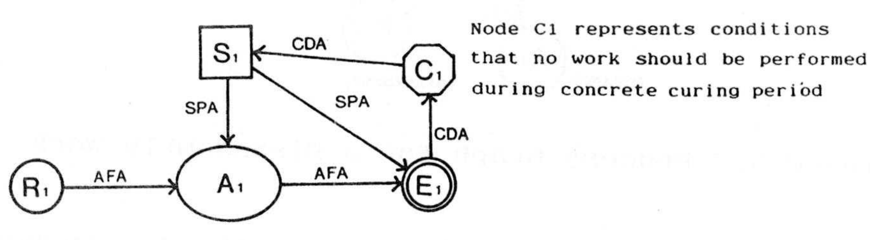


Figure 3.9 Process Graph for Conditions

4. Construction Planning in Expert Systems

4.1. Retrieval of Work Package

The first stage to be required for construction planning is the preparation of the information defined by specifications, drawings, site conditions and other constraints. The Advanced Process Graph will serve as a well-defined data structure for such information.

The specifications and drawings are transformed into Building element nodes and several arrows, which indicate the location. The site conditions and other constraints are transformed into condition nodes and condition arrows.

The second stage of construction planning is the retrieval of work packages that are necessary to complete the construction project. Each work package contains the information on what type of activity is required, and on what type of resource should be prepared or procured.

The retrieval of a work package is carried out with the key indicating the building element that the work package produces. Figure 4.1 illustrates the retrieval process of the work package (W1) which is required to produce the building element (E1).

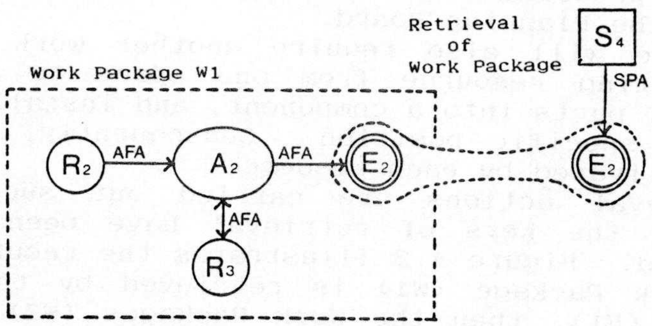


Figure 4.1 Retrieval of Work Package (W1)

4.2. Alternatives of Work Packages

The retrieval of a work package for a builing element might result in the use of any number of alternatives in the knowledge base. Therefore, the expert system should apply the proper rules for evaluating the alternatives.

Figure 4.2 illustrates three alternatives of the work package for the building element (E1). In a simple case, only the cost will be a criterion to evaluate the alternatives. In a complicated case, however, consideration should be given to the work package retrieved for other building elements. The Process Graph in the Planning Board contains several alternatives, given in the form of a tree structure, for later evaluation.

4.3. A Chain of Retrievals

When the planning board has a building element, several retrieval actions are activated. After evaluation, only one work

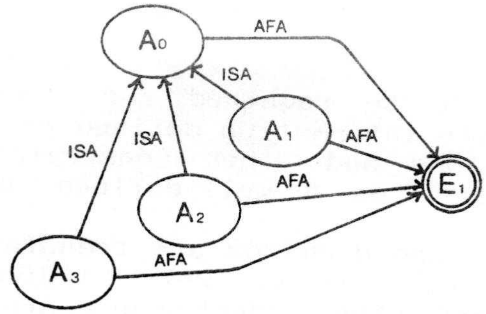


Figure 4.2 Alternatives of the Work Packages

package alternative is left for the building element. This retrieval process presents a work package consisting of an activity and resources in the planning board.

4.3. A Chain of Retrievals

When the Planning Board has a building element, several retrieval actions are activated. After evaluation, only one work package alternative is left for the building element. This retrieval process presents a work package consisting of an activity and resources in the Planning Board.

Each resource will also require another work package, for example, transporting resource from one space to another, pre-assembling work of parts into a component, and installing temporary equipment in the specific position. Consequently, the retrieval action will be activated by each resource.

Those retrieval actions are carried out successively and recursively until the keys of retrieval have been exhausted in the Planning Board. Figure 4.3 illustrates the recursive process, in which the Work Package (W1) is retrieved by the key of the building element (E1), then the Work Packages (W2) and (W3) are retrieved by the key of the Resources (R1) and (R2) successively.

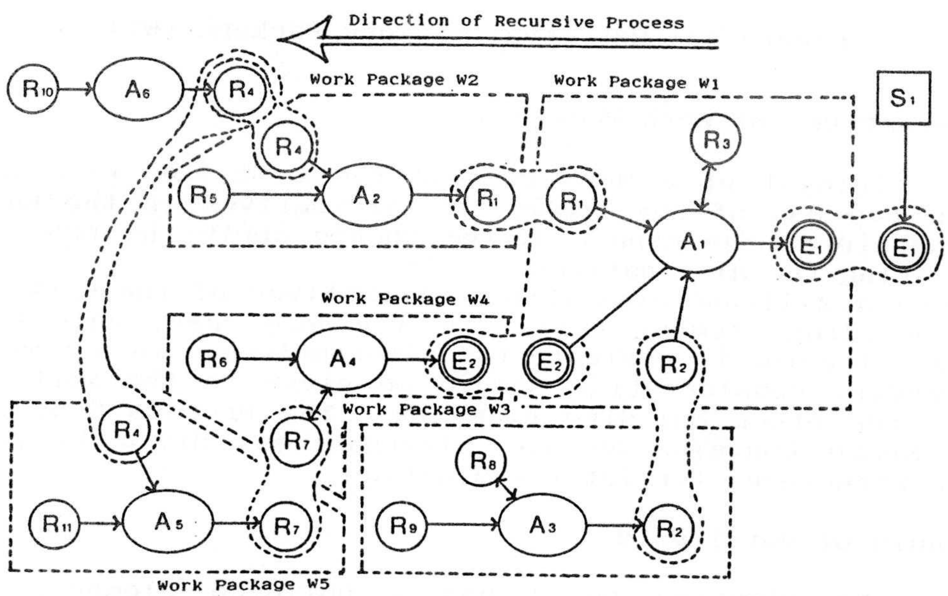


Figure 4.3 Recursive Process for Retrieval of Work Packages

The recursive actions of retrieval will reproduce all of the work packages required to complete the whole project. Construction plans in the Planning Board are increased as a breeder reactor with the knowledge bases of planning procedure and construction method.

4.4. Precedences between Activities

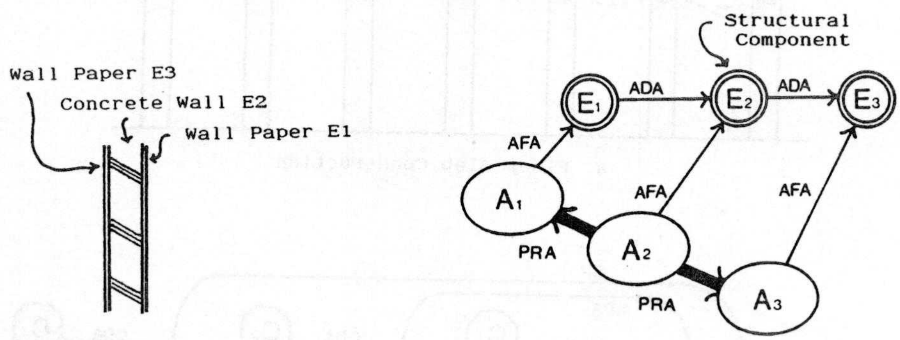
4.4.1. Precedences due to Building Elements

The positions of building elements are essential to determine the precedence between activities. The rules which affect the precedence are classified into two types.

One rule is adopted where a building element is placed on the surface of another building element - i.e., a wall consists of the structural components and finishing layer. To complete the wall, the structural component should be produced before the finishing layer is applied.

The other rule is adopted where a building element is placed a top another building element - i.e., a floor is positioned a top columns. To construct the building frame, the columns should be set before the floor slab.

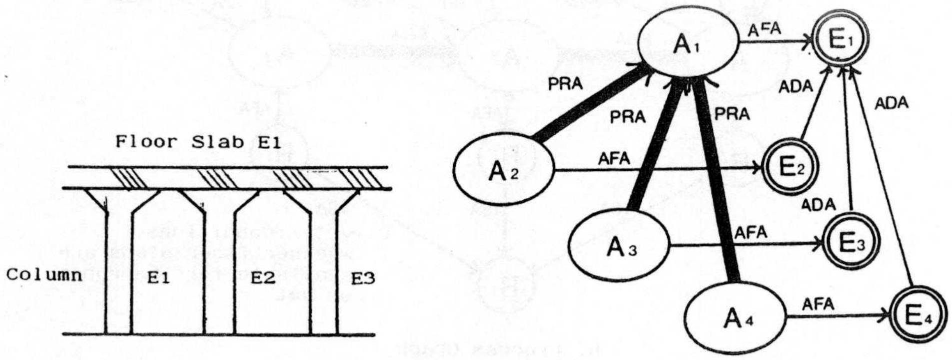
Figure 4.4 shows the rules which define the precedence of activities in wall construction. Figure 4.5 shows the rules which define the precedence of activities in building frame construction.



a. Section of Wall

b. Process Graph

Figure 4.4 Precedences between Wall Construction Works



a. Section of Floor Slab

b. Process Graph

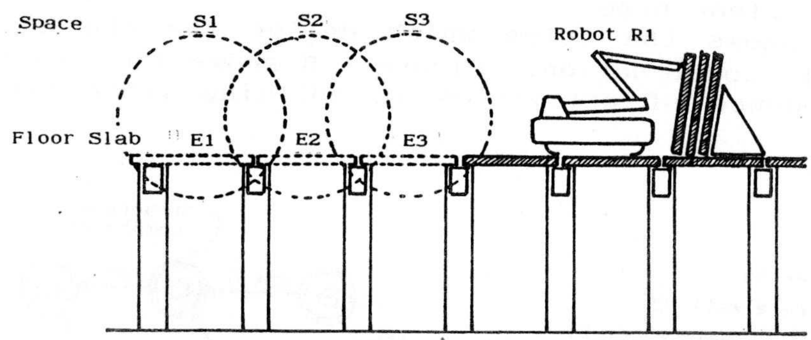
Figure 4.5 Precedences between Building Frames Construction Works

4.4.2. Precedences due to Space

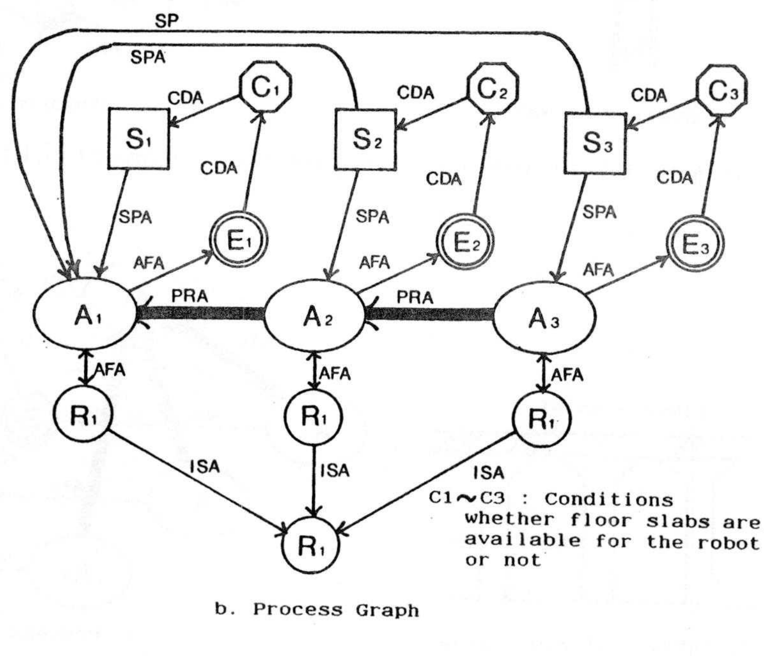
The conditions in a given space will affect work performance. In case an activity changes conditions in the space, it will influence the sequence of activities. For example, an activity involving the setting of ceiling boards by a robot moving on the floor should precede the finishing of the floor, because the motion of the robot might damage the floor surface.

Figure 4.6 illustrates a group of activities which set slab panels. A robot must move on the slab panels just installed while setting subsequent panels. Therefore, each activity should be carried out in a certain sequence according to whether or not slab panels exist on its route.

Space is confined to a limited area, so activities which could be done in the same space are restricted to a certain number due to congestion.



a. Floor Slab Construction



b. Process Graph

Figure 4.6 Precedences between Floor Slab Construction Works

4.4.3. Precedences due to the Usage of Resources

At a construction site, certain temporary items of equipment such as robots, scaffoldings, stages and cranes are installed for use during a specific period. To make construction process plan for these, it should be taken into account that the activities using such equipment must start after installation and finish before disassembly and removal.

Figure 4.7 shows the process, where activity (A1) brings in and installs a crane, activity (A2) lifts materials with the crane and activity (A3) disassembles and removes the crane. The precedences between three activities will be deduced from the rules described above.

When an activity uses materials which must be produced by a previous activity, the sequence is obvious.

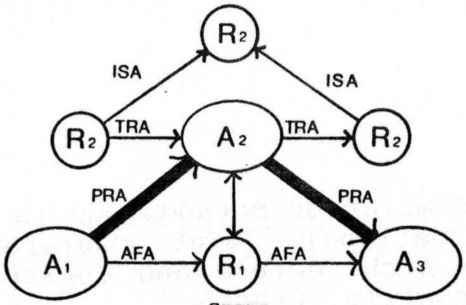


Figure 4.7 Precedences due to Crane Usage

4.4. Precedences due to Resource Allocation

Activities which have no precedences due to the abovementioned rules can be performed simultaneously. In cases where the activities require use of the same robot at the site, the order of use is determined by the difficulties of transporting the robot. Furthermore, the nature of each activity such as duration, earliest start time, total float and free float should be taken into account.

Figure 4.8 illustrates three activities which use the same type of robot. Activities (A1) and (A3) are performed in space (S1), while activity (A2) is performed in space (S2). When there is only one robot available at the site, the order of activities will be performed as A1 → A3 → A2.

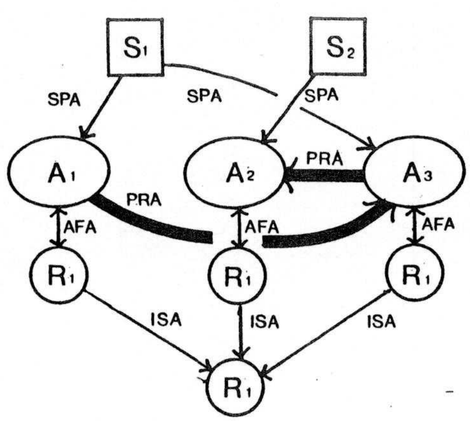


Figure 4.8 Precedences due to Resource Allocation

5. Conclusion

To develop an expert system, it is essential for us to recognize that no artificial intelligence methodology can be relevant to every possible application in the world. In the domain of construction planning, Process Graph is one of the powerful methodologies which serve as a data structure for knowledge of construction planning procedures and construction method. It is also capable of promoting the sophisticated inferences required for construction planning.

• The notations and rules on Process Graph described here are some of the primary parts which will be required by an experienced construction manager. However, the author believes that the Process Graph offers so consistent a data structure that most rules for construction planning can be effectively modeled into the graph.

Reference

1) Naruo Kano : "Simulation Methodology in Construction Process", International Joint Conference on CAD and Robotics in Architecture and Construction, June 25-27, 1986, Marseille, France