CONSTRUCTION PLANNING BY A ROBOT

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1. Introduction

Today, construction is one of the most important areas in production activities. It helps the energy problem with atomic and hydro-electric plants, the transportation problem with long span bridges, and business activities with high-rise buildings.

Many studies have been done to improve the efficiency of construction activities such as work study and method improvement.[1),2)] In recent years research on robotics in construction has emerged and several types of robots have been applied at construction sites.[3),4)]

In the near future, we need intelligent types of construction robots which will have the ability of making a proper construction plan as well as executing the activities automatically.

In this paper, our attention will be focused on the process of robot generated construction plans.

A suitable plan for construction activities will greatly depend on the situation surrounding robotized construction works and how the work must be executed. Therefore, compared with industrial robots, robots for construction sites particularly need the ability to generate promptly a suitable alternatives of plans, such as methods and precedence of activities due to the situation in existence before each execution.

The overall situation surrounding activities would be grasped with ease by a construction engineer. Due to a lack of pattern recognition ability, a robot has to gather an enormous volume of data through its sensors in order to grasp the same situation. Then, a robot has to define implicitly the situation of activities as ill-structured problem.[5)]

Furthermore, in a construction robot, a limited capacity computer (micro computer) will be installed due to cost, weight and volume. In consequence, the robot will only be able to absorb a part of the data through sensors. It cannot generate the optimal alternative for a plan using mathematical optimization techniques due to the small memory capacity and time restraints.

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The author points out that a robot has to break down the entire construction plan into sub-plans, then generate one or more alternatives of each sub-plan to reduce the complexity of the planning activities.

For generating a proper alternative of a construction plan, a robot should recognize which part of the plan would be more important and which less important. This is essential for deciding how to allocate its time and memory to each planning activity. Also, it should recognize which part of plan must be made in advance and what precedence or priority relationships exist among the sub-plans.

2. A System Approach to Construction Plan

2.1. Structure of Construction Plan

a. Element of Construction Plan

To generate a plan, we usually break down the plan into sub-plans. This is done if an entire plan is too complex to understand and generate proper alternatives simultaneously. Each sub-plan will be broken down small enough to seize its goal and optimize the alternatives.

The author defines a sub-plan as an elemental plan against the entire plan. The elemental plan is classified in the following two types.

1) Exploration and investigation for conditions of construction work
2) Plan for construction work

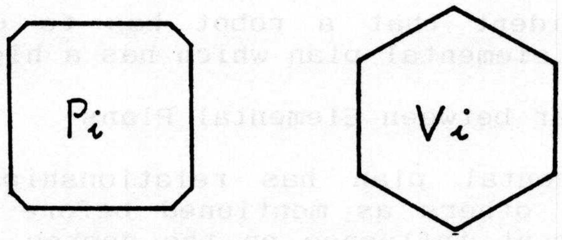
The construction planning could be defined as a set of intelligent activities in which a robot explores the work conditions and investigates this data, then confirms the proper plan of construction works.

b. Interacting among Elemental Plans

An alternative of an elemental plan on construction works might be affected by that of another elemental plan. For instance, the method of excavation work will be affected by soil conditions at the site. The method of excavation work will also affect the method of other construction activities. For generating elemental plans, a robot must not disregard for the interactions among them.

c. Presentation of Construction Plan with a Graph

To figure out the structure of an entire plan, it is useful to express the construction plan with a graphic model. In a graph, an elemental plan is represented by a node notation shown in Fig.1, and an interaction between elemental plans is represented by an arrow notation shown in Fig.2, the direction of which is indicating the way of influence.



a. Plan of Work b. Exploration of Condition

Figure 1. Representation for Elemental Plan

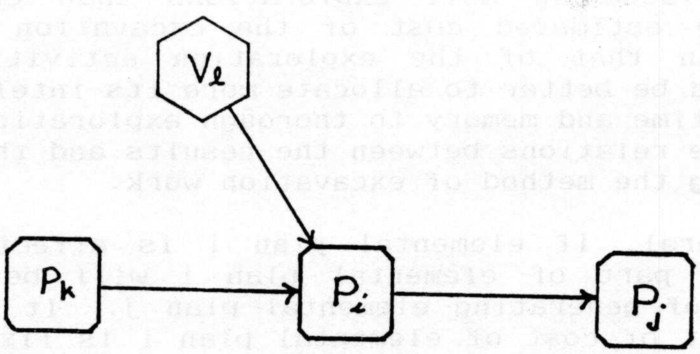


Figure 2. Representation for a Relationship

2.2. Evaluation of Plan

a. Cost of an Elemental Plan

The degree of importance of each elemental plan in an entire plan will depend on the type of construction, the site conditions, and the activities themselves.

To express the degree of importance of an elemental plan, the author employed the estimated cost on the construction work which the elemental plan concerns. Besides the estimated cost, the duration, and the engineers' priorities would be applied, if available.

In order to generalize the degree of importance on each elemental plan, the cost is expressed as the ratio to the total construction cost. The cost Ci on elemental plan i can be shown as Equation (1).

$$C_i = M_i \; / \; M \qquad (1)$$

where,
C_i : Cost of elemental plan i
M_i : Estimated cost of a work which elemental plan i concerns.
M : Total cost of construction works

It is evident that a robot has to devote more attention in planning an elemental plan which has a higher cost value.

b. Cost Transfer between Elemental Plans

Each elemental plan has relationships such as cause and effect between others as mentioned before. These relationships will have a great influence on the degree of importance of each elemental plan. For examle, suppose that the method of excavation work is greatly dependent on the condition of soil underground. It means that when the results of exploration on the soil conditions have been evaluated the planned method of excavation work may be validated as correct. It is evident that more importance should be placed on soil explorations than excavation plans, although the estimated cost of the excavation activities will be more than that of the exploration activities. Therefore, a robot would be better to allocate more its intelligent resources such as CPU time and memory to thorough exploration of soil conditions and the relations between the results and the methods rather than planning the method of excavation work.

In general, if elemental plan i is affected by elemental plan j, the part of elemental plan i will be confirmed as a consequence of generating elemental plan j. It could be assumed that the part of cost of elemental plan i is fixed in generating elemental plan j. Therefore, elemental plan j should be assigned the cost which is transferred from elemental plan i in addition to the cost estimated for the own plan, as shown in Fig.3.

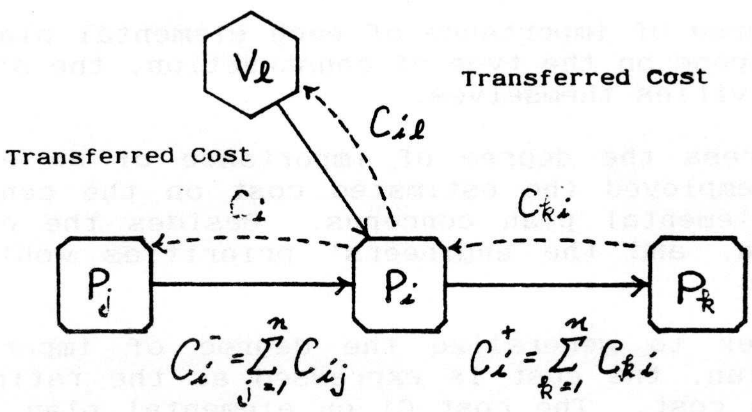


Figure 3. Transferred Cost between Elemental Plans

The cost tranferred could be assumed to be in proportion to the weight of influence from elemental plan j to elemental plan i. The weight of influence will be given by way of a system approach to a construction plan by construction engineers. The weight has a value between zero and one. The summation for elemental plan i as shown in Equation (2) means the proportion of planning which will be confirmed in other elemental plans, the rest of which must be made in elemental plan i.

$$\sum_{j=1}^{n} W_{ij} \leq 1 \qquad (2)$$

where,

W_{ij} : Weight of influence on a relationship from elemental plan j to elemental plan i

n : The number of elemental plans

c. The Degree of Importance for an Elemental Plan

As mentioned before, a part of the cost on each elemental plan is transferred into other elemental plans in proportion to the weight of influence of each elemental plan. Therefore, in order to evaluate the elemental plan, a robot has to take account of the cost transferred from other elemental plans in addition to the cost on the own plan.

The degree of importance for elemental plan i would be defined as the cost which a robot could confirm in generation the elemental plan i. This cost could be calculated as a total value Gi as shown in Equation (3),(4),(5).

$$G_i = C_i + C^+_i - C^-_i \qquad (3)$$

$$C^+_i = \sum_{j=1}^{n} W_{ji} (C_j + C^+_j) \qquad (4)$$

$$C^-_i = \sum_{k=1}^{n} W_{ik} (C_i + C^+_i) \qquad (5)$$

where,

G_i : Degree of importance for elemental plan i

C_i : Cost of elemental plan i

C^+_i : Total transferred cost into elemental plan i

C^-_i : Total transferred cost out of elemental plan i

W_{ji} : Weight of influence on a relationship from elemental plan i to elemental plan j

3. Sequence of Generating Elemental Plans

3.1. Precedences among Elemental Plans

To generate alternatives of an elemental plan, all of the other elemental plans which affect this elemental plan must be completed beforehand. In this manner, an elemental plan should preceed all others on which it has an influence.

If a robot generates an alternative of an elemental plan without regard to the precedence among the other elemental plans, it will have to re-generate alternatives several times due to the inconsistency among the elemental plans. However, when there is no relationship among the elemental plans, alternatives of these plans could be generated independently and simultaneously.

It is essential for a robot to figure out the process of how it generates a plan. A robot should make a plan about the process, before it generates the plans of activities. Then, a robot can more efficiently make a construction plan according to the precedences that are established through a systems approach to construction planning. Moreover, if a robot has more than two central process or units, it will be able to shorten the time for construction planning by generating plans in parallel.

The precedence between two elemental plans would be established with the following rule:

> If one elemental plan is affected by another elemental plan, the rbot must generate alternatives of these affecting plans before generating an alternative of an affected plan.

This rule indicates that the precedence between two elemental plans could be represented by the direction of influence between them. Therefore, the graph which models the structure of a construction plan also shows the precedence relationship between elemental plans if there is no link in the graph. A link is defined as a path which departs from a certain node and returns to the same node through several other nodes tracing in the direction of arrows.

Construction plans are, however, too complex to represent as a graph without any loops except in a very small plan. Therefore, it is necessary to make a methodology to establish the precedence among elemental plans in a plan which has relationships to be connected in links.

3.2. Removal of a Link

Suppose that a group of elemental plans are connected in a link as shown in Fig.4, one could not establish the precedence relations among the elemental plans because each elemental plan is affected by all other elemental plans. In the construction plan which is broken down into the elemental plan as shown in

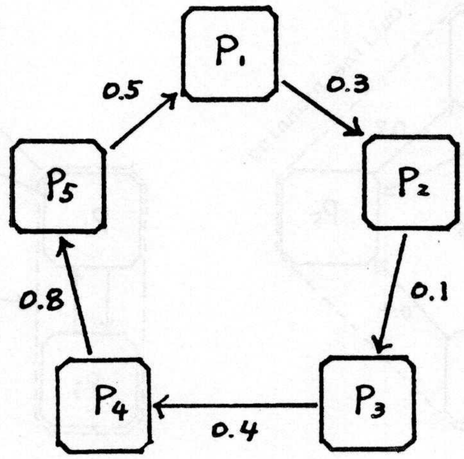


Figure 4. A Link of Relationships

Fig.4, a robot has to neglect a less important relationship (ex. 2 → 3). Then it could generate an alternative of each elemental plan successively according to the direction of influence as $P_3 \rightarrow P_4 \rightarrow P_5 \rightarrow P_1 \rightarrow P_2$. The above procedure makes it possible to detect the sequence of generating the elemental plans, but this procedure will also let a robot generate the elemental plan without taking into account all the relationships among the elemental plans. To compensate for this neglection of a relationship to be removed, a robot has to generate an outline of a group of elemental plans that are connected in the link.

With the above compensation for neglecting a relationship, a robot can generate each elemental plan successively with a micro computer, considering the influence from other elemental plans. Then it can integrate these elemental plans into an entire construction plan.

The relation to be removed must be the relation which has the least influence in the graph. The strength of influence will be expressed by the cost which is transferred through the relational arrow in the graph. This cost can be calculated in the Equation (6).

$$C_{ji} = W_{ji} (C_j + C^+_j) \qquad (6)$$

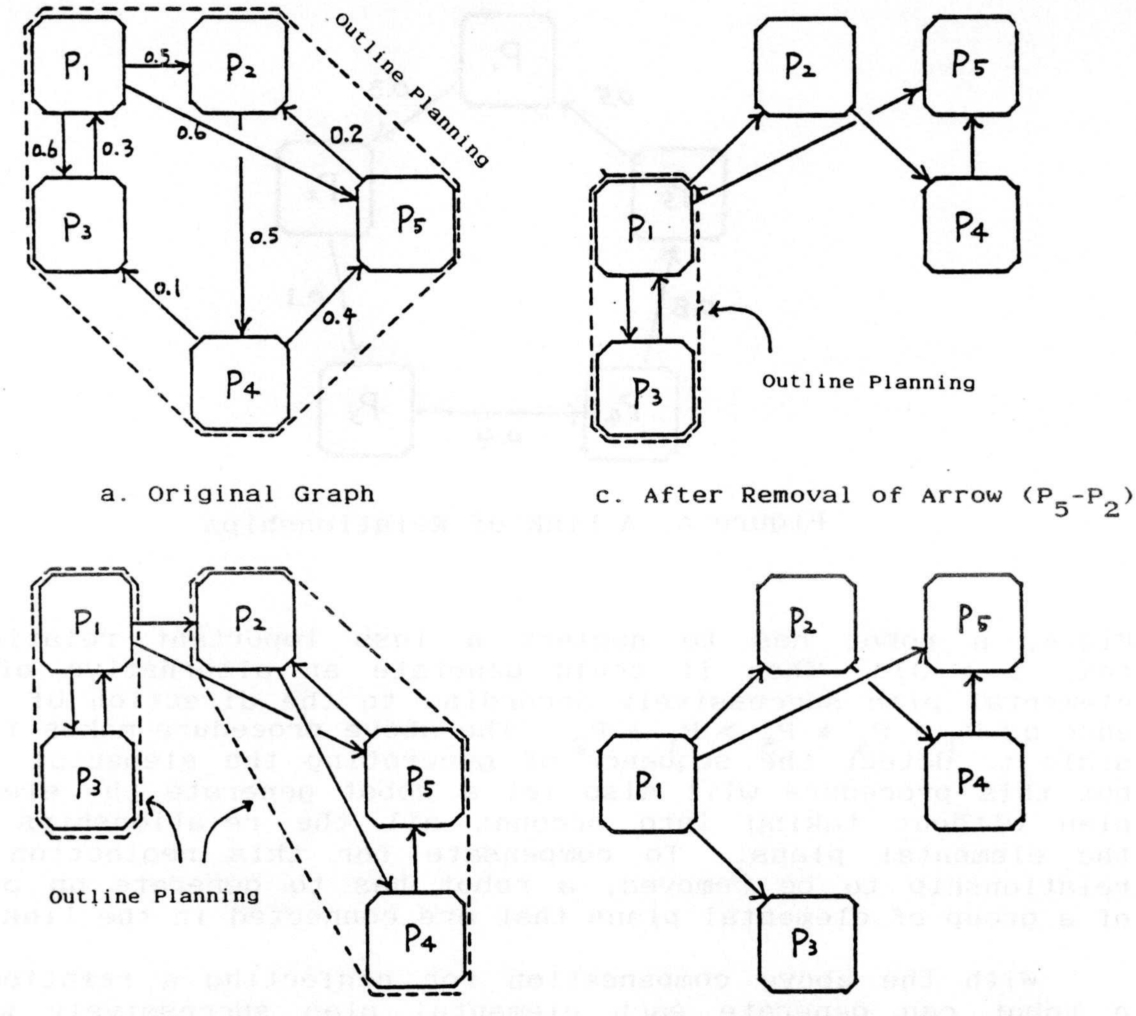
where,

C_{ji} : Transferred cost from elemental plan j into elemental plan i

W_{ji} : Weight of the influence from elemental plan i to elemental plan j

C_j : Cost of elemental plan j

C^+_j : Transferred cost into elemental plan j



a. Original Graph

c. After Removal of Arrow (P_5-P_2)

b. After Removal of Arrow (P_4-P_3)

d. After Removal of Arrow (P_3-P_1)

Figure 5. Removal of Arrows in Links

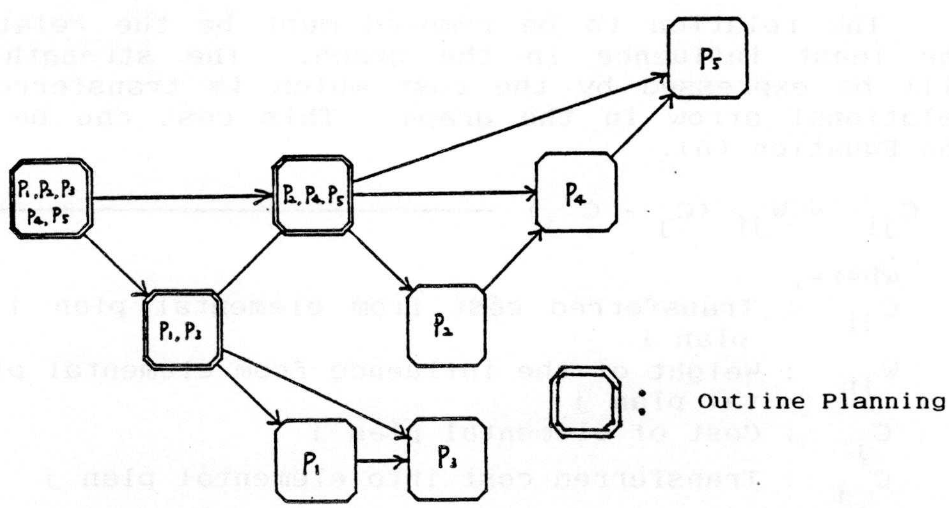


Figure 6. Network Diagram for Planning

3.3. Procedure of Establishing the Precedences among Elemental Plans

The procedure to establish the precedence is shown in the following steps:

1) To detect the links which connect elemental plans
2) If there are any links, a robot makes an outline for a group of elemental plans which exists in the links, otherwise it goes to step 4.
3) Remove a relational arrow which has the least strength of influence (transferred cost) in the links, then return to step 1.
4) Put the precedence relation on elemental plans according to the direction of influence.

Fig.5 shows those steps as an example. Fig.5.a shows the five elemental plans affecting each other and the transferred cost on each relational arrow. Since all of the elemental plans are linked, an outline for these elemental plans must be made first.

Fig.5.b shows the graph after the removal of the arrow ($P_4 \rightarrow P_3$) which has the least transferred cost (0.1). In the graph, there are still two independent links. Then, the robot must make two outlines for elemental plans (P_1, P_3), and for elemental plans (P_2, P_4, P_5).

Fig.5.c shows the graph after removal of the arrow ($P_5 \rightarrow P_2$). There can be found the precedences among elemental plans P_2, P_4, P_5, but still an outline must be made for elemental plans P_1, P_3.

Fig.5.d shows the final graph which has no link after removing the arrow ($P_3 \rightarrow P_1$).

The planning procedure could be diagrammed with the CPM Network shown in Fig.6. In this planning phase, a robot must make three outlines in addition to five elemental plans.

4. An Example of Planning Process

4.1. Excavation Work for an Office Building Substructure

The excavation work for an office building is taken as an example. This example has been prepared to illustrate how a robot develops the procedure of planning construction activities.

The construction site is located in the middle of downtown, Tokyo. The area of excavation for substructure is $1000m^2$ (40mx20m) and the depth is 10.5m deep as shown in Fig.7.

The entire construction plan forexcavation work can be broken down into twenty-one elemental plans. Eight are planning for

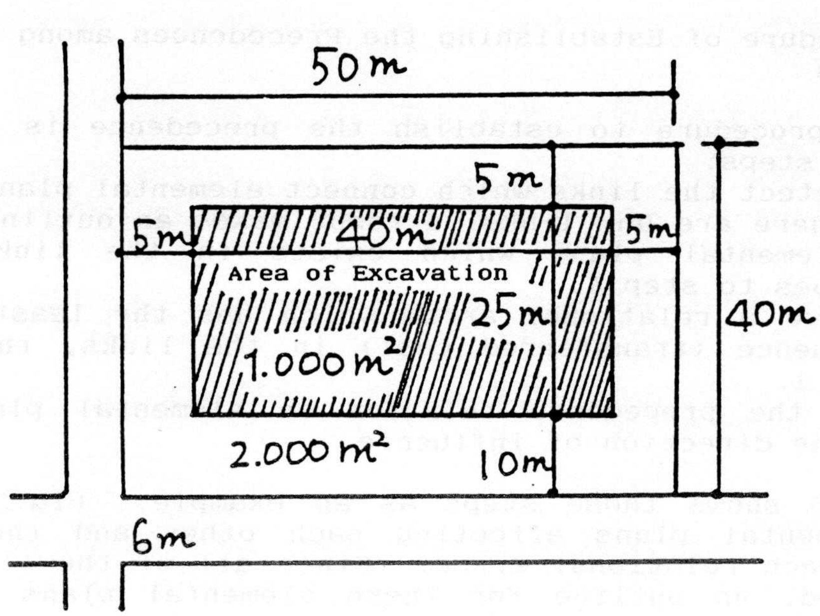


Figure 7. Layout of the Site

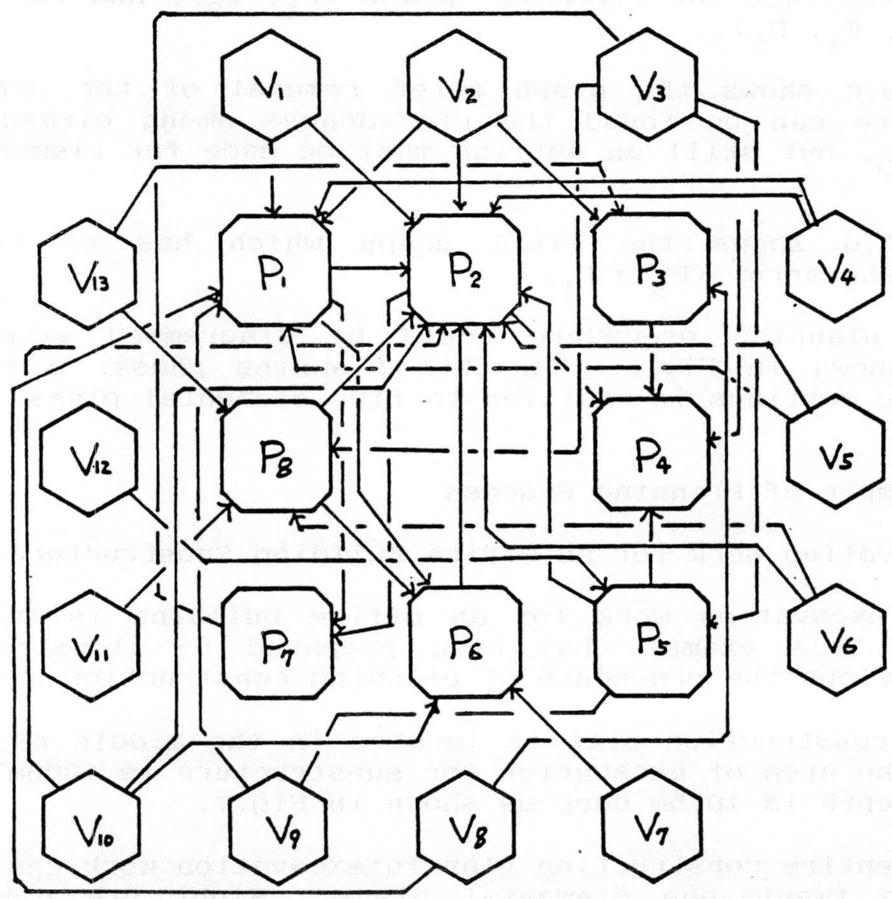


Figure 8. A Graph Representation for Planning Excavation Work (part)

Table 1. Elemental Plans to be Taken into Account in Excavation Works

Exploration for Conditions		Plan for Works	
CODE	Description	CODE	Description
V_1	1 Subsoil	P_1	1 Shoring work
V_2	2 Specification and Drawings	P_2	2 Bracing Work
V_3	3 Site Layout	P_3	3 Piling Work
V_4	4 Adjacent Buildings	P_4	4 Below-Ground-Level Scaffolding Work
V_5	5 Obstructions around the Site	P_5	5 Earth Moving Work
V_6	6 Obstructions at the Site	P_6	6 Drainage
V_7	7 Temporary Water Connection	P_7	7 Stress, Dimension and Other Measuring Activities
V_8	8 Pollution	P_8	8 Substructure Work
V_9	9 Access Roads		
V_{10}	10 Ground Water Level		
V_{11}	11 Weather		
V_{12}	12 Place to Dump Excavated soil		
V_{13}	13 Time for Completion		

Table 2. Estimated Cost for Excavation Works

Elemental Plan \ Estimated Cost	Value	Ratio
1 Shoring work	27 $¥10^6$	0.068
2 Bracing Work	12	0.030
3 Piling Work	46	0.116
4 Below-Ground-Level Scaffolding Work	18	0.045
5 Earth Moving Work	80	0.202
6 Drainage	4	0.010
7 Stress, Dimension and Other Measuring Activities	2	0.005
8 Substructure Work	207	0.523
Total	396	1.000

Table 3. Weights of Influence between Elemental Plans

	Affected Element / Affecting Element	1 Shoring Work	2 Bracing Work	3 Piling Work	4 Below-Ground-Level Scaffolding Work	5 Earth Moving Work	6 Drainage	7 Stress, Dimension, Other Measuring Activities	8 Substructure Work
Exploration for Conditions	1 Subsoil	0.15	0.15	0.04	0.01	0.02	0.06	0.03	
	2 Specification and Drawings	0.05	0.06	0.30	0.02	0.03		0.01	0.30
	3 Site Layout		0.03	0.02	0.04	0.04			0.05
	4 Adjacent Buildings	0.08	.0.06	0.02		0.01	0.04		
	5 Obstructions around the Site	0.08	0.06	0.02			0.04	0.03	
	6 Obstructions at the Site	0.03	0.06	0.04	0.01	0.03			0.05
	7 Temporary Water Connection			0.02			0.06		
	8 Pollution	0.05		0.07	0.01	0.03	0.02	0.01	0.02
	9 Access Roads	0.05			0.02	0.04			0.02
	10 Ground Water Level	0.15	0.12	0.04		0.03	0.06	0.01	0.02
	11 Weather	0.03				0.03	0.02	0.01	0.05
	12 Place to Dump Excavated soil			0.02		0.04			
	13 Time for Completion	0.03		0.07	0.04	0.04	0.02		0.07
Plan for Works	1 Shoring work		0.09			0.01	0.06	0.04	
	2 Bracing Work	0.05			0.02	0.04	0.02	0.04	0.05
	3 Piling Work	0.03	0.03		0.01	0.01			0.02
	4 Below-Ground-Level Scaffolding Work		0.03			0.04		0.01	
	5 Earth Moving Work	0.03	0.06	0.04	0.04		0.04	0.01	0.05
	6 Drainage	0.05	0.06			0.03		0.01	0.02
	7 Stress, Dimension and Other Measuring Activities								
	8 Substructure Work		0.06	0.04	0.02	0.03	0.06	0.01	
	Non-Affecting Portion	0.14	0.13	0.26	0.76	0.50	0.50	0.78	0.28

Table 4. Degree of Importance for Elemental Plans

Exploration for Conditions		Plan for Works	
Description	Degree	Description	Degree
1 Subsoil	0.036	1 Shoring work	0.011
2 Specification and Drawings	0.220	2 Bracing Work	0.010
3 Site Layout	0.044	3 Piling Work	0.035
4 Adjacent Buildings	0.017	4 Below-Ground-Level Scaffolding Work	0.044
5 Obstructions around the Site	0.015	5 Earth Moving Work	0.123
6 Obstructions at the Site	0.047	6 Drainage	0.018
7 Temporary Water Connection	0.005	7 Stress, Dimension and Other Measuring Activities	0.004
8 Pollution	0.033	8 Substructure Work	0.152
9 Access Roads	0.026		
10 Ground Water Level	0.047		
11 Weather	0.038		
12 Place to Dump Excavated soil	0.013		
13 Time for Completion	0.063		
Total	0.603	Total	0.397

Table 5. Relationships to be Removed

no.	relation	no.	relation	no.	relation	no.	relation
1	$P_3 \rightarrow P_4$	6	$P_3 \rightarrow P_2$	11	$P_3 \rightarrow P_1$	16	$P_5 \rightarrow P_2$
2	$P_2 \rightarrow P_6$	7	$P_4 \rightarrow P_2$	12	$P_5 \rightarrow P_1$	17	$P_8 \rightarrow P_2$
3	$P_2 \rightarrow P_4$	8	$P_1 \rightarrow P_6$	13	$P_1 \rightarrow P_5$	18	$P_5 \rightarrow P_3$
4	$P_8 \rightarrow P_4$	9	$P_8 \rightarrow P_6$	14	$P_3 \rightarrow P_5$	19	$P_8 \rightarrow P_3$
5	$P_5 \rightarrow P_6$	10	$P_5 \rightarrow P_4$	15	$P_2 \rightarrow P_1$	20	$P_8 \rightarrow P_5$

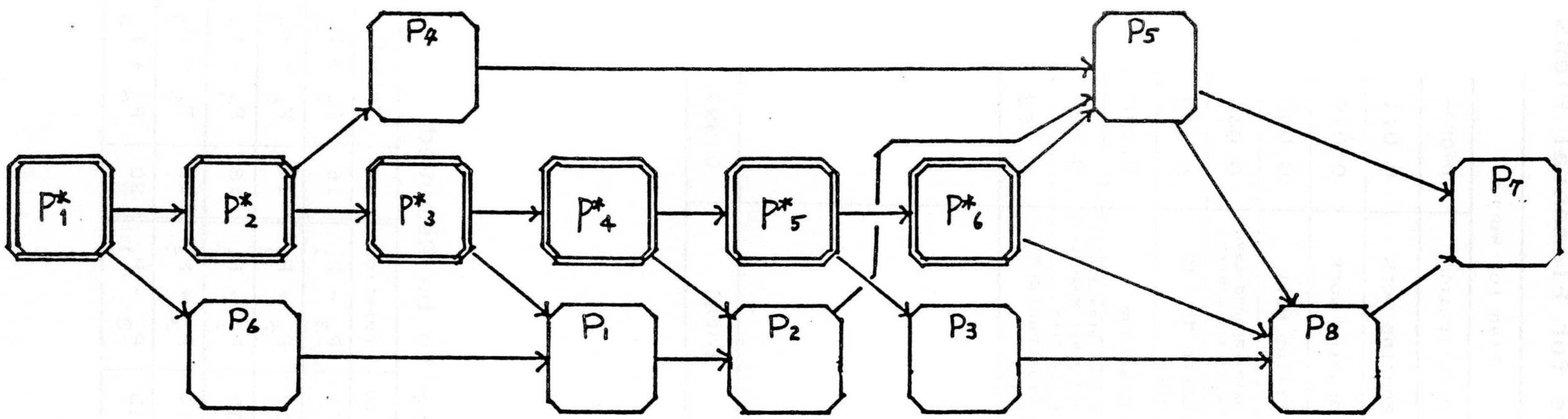


Figure 9. Network Diagram for Planning Excavation Works

Plan for Works

CODE	Description
P_1	1 Shoring work
P_2	2 Bracing Work
P_3	3 Piling Work
P_4	4 Below-Ground-Level Scaffolding Work
P_5	5 Earth Moving Work
P_6	6 Drainage
P_7	7 Stress, Dimension and Other Measuring Activities
P_8	8 Substructure Work

Outline Planning to be Added

Outline Planning	Elemental Planning
P^*_1	$P_1 \sim P_6$, P_8
P^*_2	$P_1 \sim P_5$, P_8
P^*_3	$P_1 \sim P_3$, P_5, P_8
P^*_4	$P_2 \sim P_3$, P_5, P_8
P^*_5	P_3, P_5, P_8
P^*_6	P_5, P_8

works and thirteen are exploring in Table 1. According to the nature and structure of excavation works, we defined the relationships among elemental plans as a graph in Fig.8.

We estimated the cost of a work which each elemental plan is concerning with in Table 2. The cost of exploration is assumed to be zero.

Table 3 shows the relation matrix where an element indicates the weight of influence from elemental plan i to elemental plan j.

The importance of each elemental plan could be measured with the cost on the elemental plan in Equation (3) described before. The degree of importance on each elemental plan is calculated in Table 4. It is clear that the most important activity of elemental plans is the exploration of specifications and drawings (0.220). This means that the check of specifications and drawings is the most essential for planning the excavation works. The second is the plan for substructure work (0.152) and the third is the plan for earth moving work (0.123).

Finally, we establish the precedence network which represents the procedure of planning for excavation works of an office building in Fig.9. Table 5 shows the relationship which has been removed in establishing these precedences.

5. Conclusion

The process of planning all activities for a construction site will vary in accordance with the activities' size, type, and number. Therefore, to plan the work which is large and complex, a robot has to make a plan about the process of how it generates each elemental plan. This is referred "meta-planning".

By the methodology described here, a robot used for planning will be able to efficiently allocate its intelligent resources such as CPU time and memory. Allocation will be based on the degree of importance of each plan and the network diagram.

The author has proven by the above example that by using the procedure described in this paper, a robot can generate efficiently suitable alternatives of construction activities with varying situations surrounding the site. In conclusion, a robot can make a large plan with a micro computer in a short time.

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