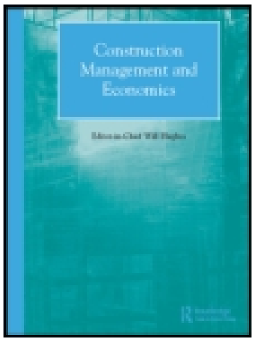

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A model for the selection of the optimum crane for construction sites

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This paper presents a method of locating a crane on a construction site using mathematical techniques. The optimum location and choice of the crane on a site is seen as one of the most important parts of construction planning. It proposes the algorithm which can define the least expensive cranage cost (the total cost of the hire, assembly and dismantling) by calculating the combined use of different cranes, such as truck crane, crawler crane, travelling based tower crane or fixed base tower crane. Conclusions are drawn as to the relevance of the application of the model to construction projects.

Keywords: Crane location, all-zero-one integer programming, dynamic programming, combination of cranes, construction management

Introduction

Construction projects have become more complex and costly in recent years. However, decision making during the initial planning and management strategy development stages still depends primarily on experience, intuition or hunch. This is probably because there have been few rational approaches to decision making developed from management science research. Thus many of the decisions in the construction industry vary from one manager to another even given that the basic problem is the same. However, there are many decision processes upon which there is an underlying logical decision process which is constrained by physical factors. The construction site and the cranes which are available, for example, provide such a decision process. This type of problem is eminently suitable for solution using management science techniques. This paper proposes a model for determining the most suitable crane location and choice of crane to give the most economic solution.

The approach (Fig. 1a) uses four stages to: (a) define the basic assumptions and constraints used to create the model, (b) use a model to examine the suitability of a mobile crane in terms of lifting capacity, working range and service-height limitations, (c) use a model to examine the suitability of a fixed base tower crane in terms of lifting capacity and working range, (d) develop a list of the most suitable cranes for each floor of the building. For each crane so selected, a calculation of the cost can be made enabling the selection of the least cost option.

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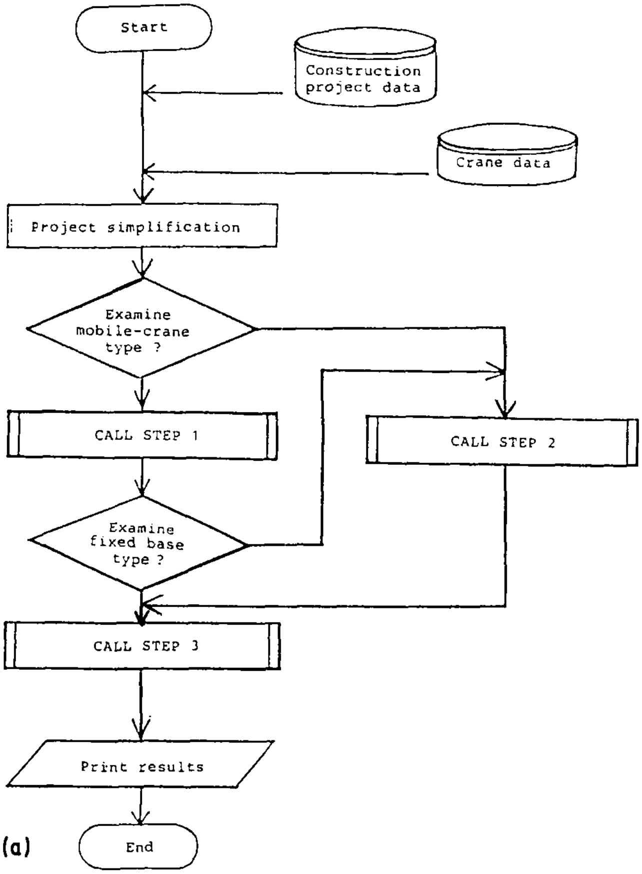


(a)

Fig. 1. (a) Total decision flow diagram. (b) Examination of the selection of a mobile crane. (c) Examination of fixed base tower crane combination. (d) Calculation of the minimum crane cost.

The constraints and assumptions used to generate the model

A number of assumptions and constraints have been defined in order to create the basic model:

1. 'The most suitable crane' means obtaining the least cost option (the costs include the total hire cost, the assembly and dismantling of the crane, the running costs and the base).
2. The hire cost of cranes is calculated as the cost per working day from commencement of working to completion of working.
3. The loads to be lifted and the maximum load are predetermined.
4. Total lifting time is not unduly affected by the variability of lifting speed and slewing speed of the various crane types available.

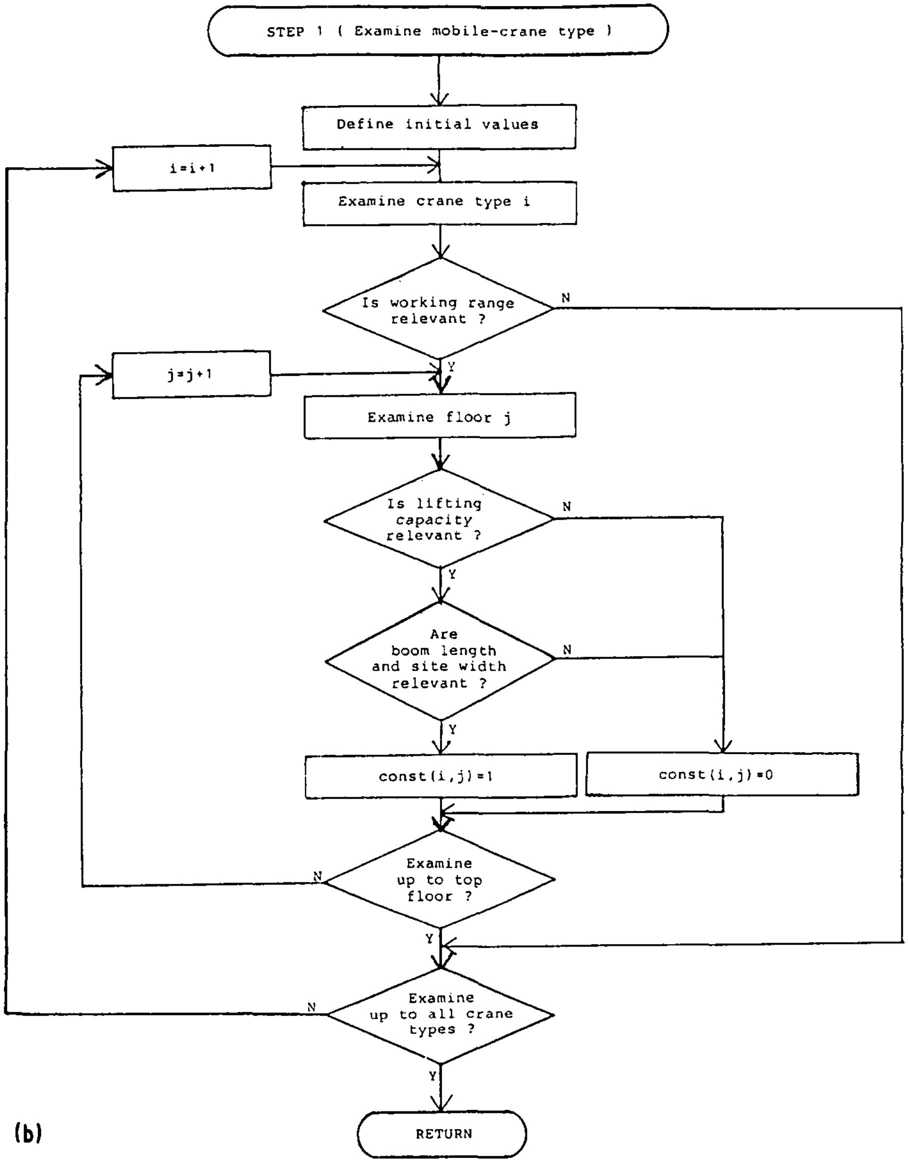


Fig. 1. Continued.

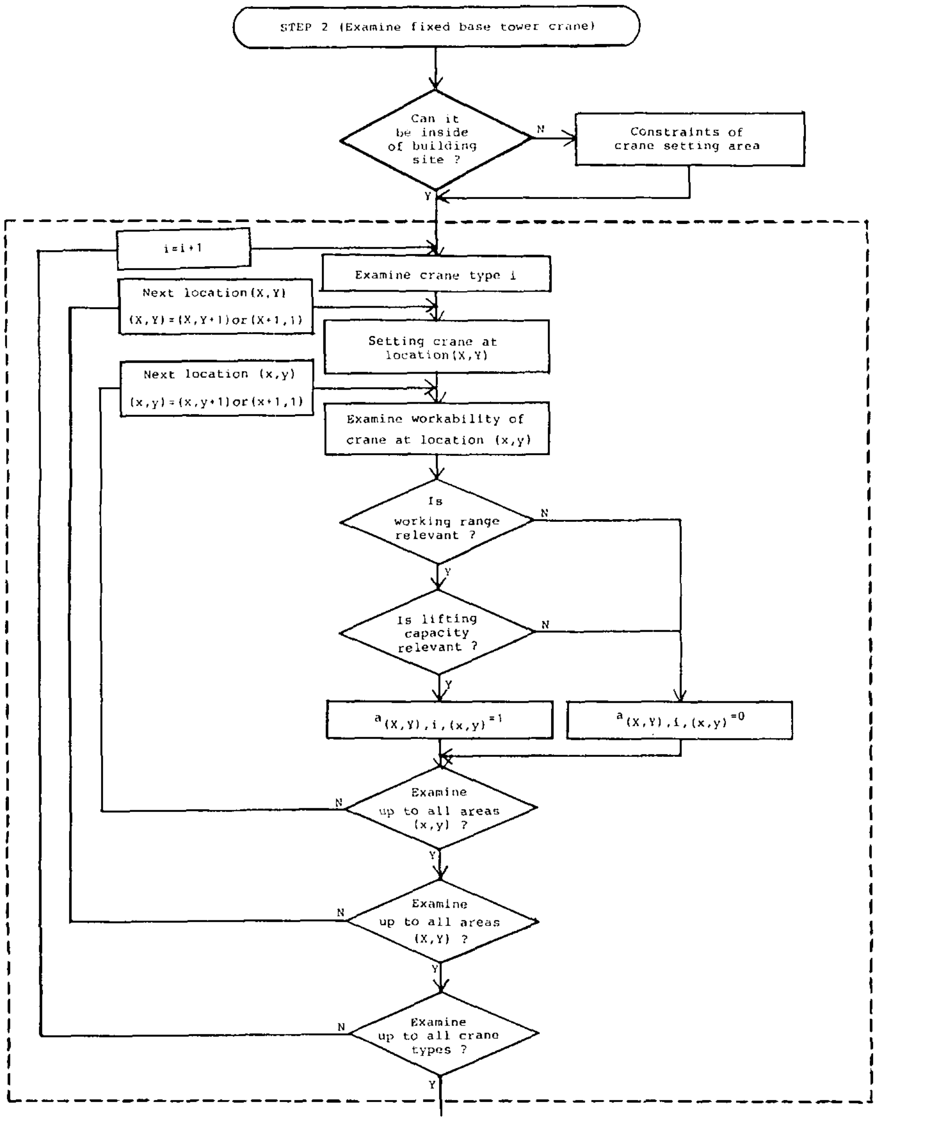
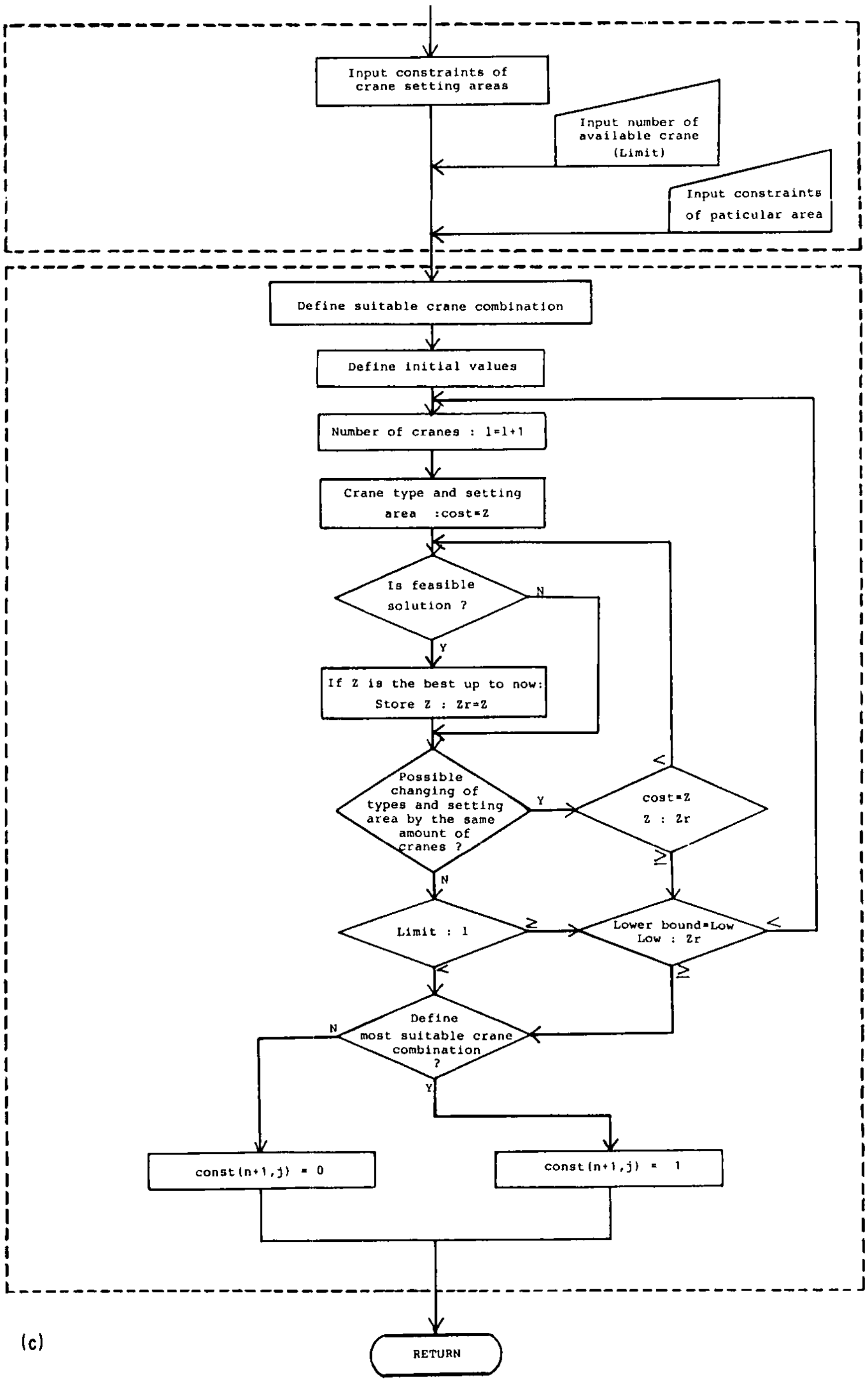
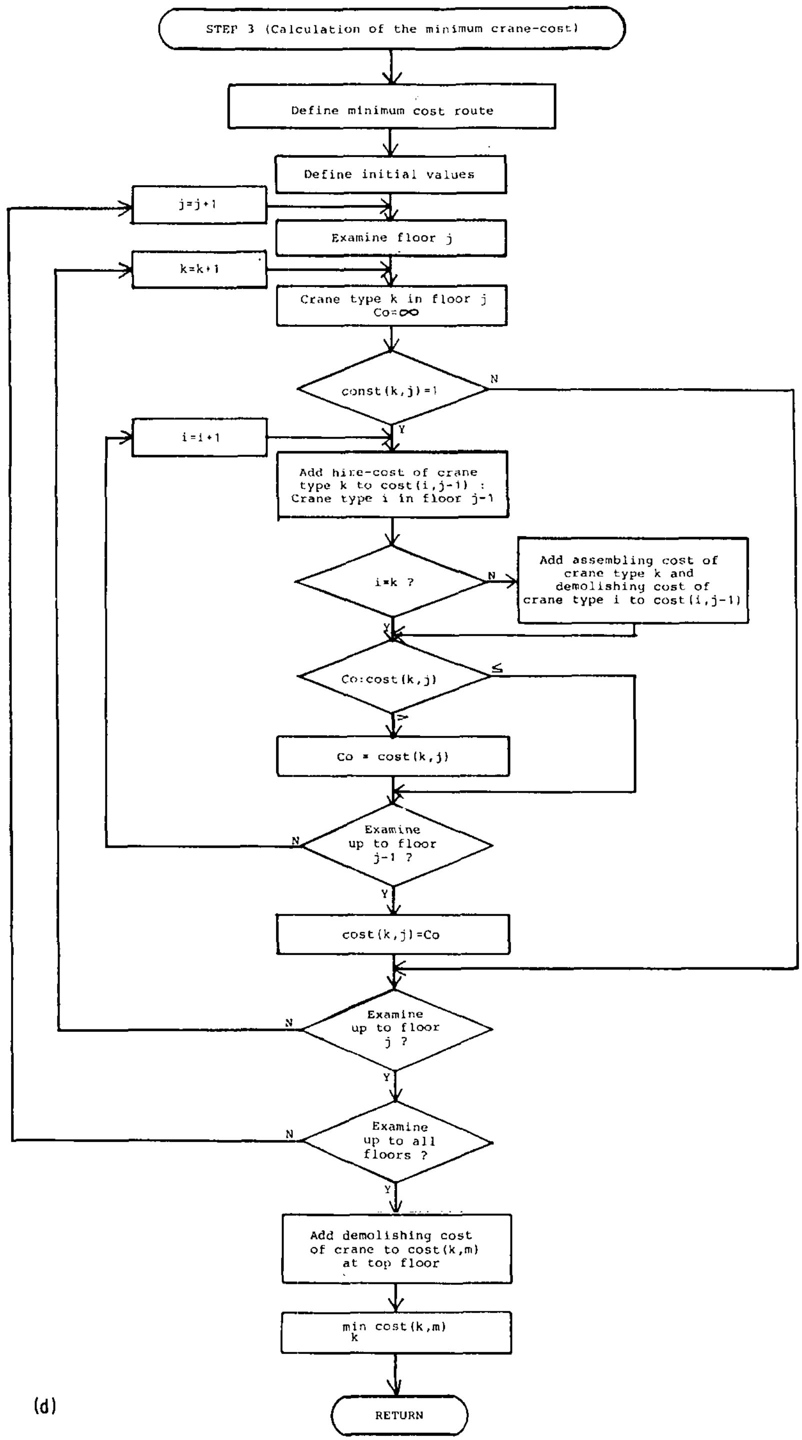


Fig. 1. Continued.



(c)

Fig. 1. Continued.



(d)

Fig. 1. Continued.

5. The crane types discussed in this paper are detailed in Table 1 and fall into three categories, crawler crane, telescopic truck crane and tower crane. The tower crane section can be further subdivided into three types: fixed base, climbing base and travelling base. However, for simplicity, crawler cranes, telescopic truck cranes and travelling base tower cranes are all called mobile cranes, and fixed base and climbing base tower cranes are all called fixed base tower cranes.

6. It is assumed, for the purpose of calculation, that there is no service-height limitation for fixed base tower cranes, since, by using an intermediate support frame, the crane can be supported for the height of the building.

7. When considering mobile cranes, only one crane can be used to construct each floor.

8. The selected crane must provide 100% lifting cover over the plan area of the building.

9. When considering fixed base tower cranes, more than one crane might be used at the same time, because one fixed base tower crane may not give 100% cover.

10. The selected crane must be capable of lifting the maximum load at the required radius.

11. All of the levels over which loads are to be lifted should be within the crane's service height.

12. The total crane cost, z, is defined as:

$$z=\sum_{i=1}^{n}\sum_{j=1}^{m}(C_1\cdot d_{i,j}\cdot f_{i,j}+Q_i\cdot b_j\cdot f_{i,j}) \tag{1}$$

Table 1. Available cranes.

Crane	Crane type	Boom length (m)	Weight range (m)	Capacity (ton m)	Tower height (m)	Hire-cost ($)	Assembly cost ($)	Dismantling cost ($)
Truck crane	01	24	16	22	0	30 000	0	0
	02	30	20	28	0	50 000	0	0
	03	35	30	30	0	60 000	0	0
	04	52	60	40	0	90 000	20 000	10 000
	05	60	85	45	0	150 000	40 000	20 000
	06	83	131	61	0	210 000	40 000	20 000
Crawler crane	07	31	26	20	0	40 000	60 000	30 000
	08	43	30	32	0	60 000	60 000	30 000
	09	52	31	34	0	80 000	60 000	30 000
	10	58	54	38	0	140 000	80 000	50 000
	11	81	162	54	0	220 000	80 000	50 000
Crawler tower crane	12	20	81	20	36	80 000	100 000	60 000
	13	22	88	22	39	90 000	100 000	60 000
	14	31	144	31	41	100 000	120 000	80 000
Travelling base tower crane	15	34	120	30	32	100 000	1 000 000	400 000
	16	44	120	40	33	160 000	1 200 000	400 000
Static base tower crane	17	30	35	30	100	40 000	240 000	160 000
	18	32	60	32	100	50 000	240 000	160 000
	19	34	120	30	100	80 000	280 000	200 000
	20	44	120	40	100	130 000	280 000	200 000

where C_i is the hire cost/day of crane type i, $d_{i,j}$ is the working time in days for floor j using crane type i, Q_i is the assembly and dismantling cost for crane type i. $f_{i,j} = 1$ or 0 where $1 =$ floor j is constructed with crane type i and $0 =$ otherwise. $b_j = 1$ or 0 where $1 =$ floor $(j-1)$ and floor j is not constructed with the same crane and $0 =$ otherwise. i is the crane type number, $i = 1, 2 \ldots n$ and n is the number of different crane types. j is the floor number, $j = 1, 2 \ldots m$ and m is the number of floors.

Since the objective function is to try to minimize the total crane cost, z, also one single floor should be construction with only one type of crane; so the constraint can be considered as:

$$\sum_{i=1}^{n} f_{i,j} = 1 \qquad j = 1, 2 \ldots m \tag{2}$$

The problem is first to examine whether floor j can be constructed with crane type i or not, and then to decide whether or not floor $j(1-m)$ is constructed with crane type i, for the purpose of minimizing the crane cost. Therefore, the main point is to decide whether $f_{i,j}$ equals 1 or 0.

The procedures for deciding the value of $f_{i,j}$ will be described using the decision models in Stages 2 and 3. The Stage 2 model is for mobile cranes, assuming that for buildings of low height a mobile crane is the more suitable type of machine. The Stage 3 model is for tower cranes and is more applicable where the building size is beyond the capability of the mobile crane.

A model for the selection of a mobile crane

The specification of each crane in terms of its working range, lifting capacity and service height is set against the project conditions and the location of the loads in the building in order to determine the variable const (i, j) as shown in the decision flow chart in Fig. 1b.

$$\text{const } (i, j) = 1 \text{ or } 0$$

where $1 =$ floor j can be constructed with crane type i (namely, crane type i simultaneously satisfies the four conditions of Equations 3–6) and $0 =$ otherwise.

The following definitions will be used

$L_Y =$ width of site in axis Y direction (see Fig. 2)
$Y_i =$ location of crane type i in axis Y direction
$H_j =$ height from floor 1 to floor j
$h_i =$ maximum tower height of crane type i
$L_{Bi} =$ maximum boom length of crane type i
$R_i =$ maximum working range of crane type i
$W_{(x,y),j} =$ maximum lifting load of floor j at location (x, y)
$W_{Yi} =$ lifting capacity of crane type i at location Y_i
$D =$ width of building in the direction of the Y axis
$W_{y,j} = \max_x [W(x, y), j]$; maximum lifting load of floor j at location $(1, y), (2, y) \ldots (x, y)$

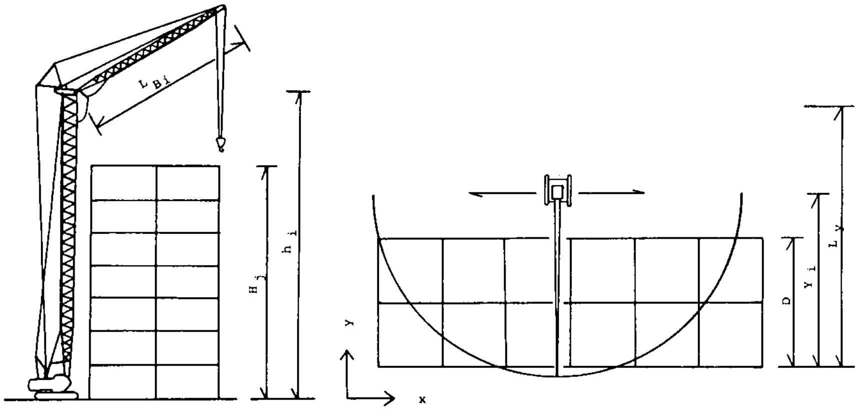


Fig. 2. Construction project model of site and mobile crane.

The model of the construction site and the building with a mobile crane

The simplified model of a construction site and building is shown in Fig. 2. It shows the inter-relationship between the building, the width of the site and the working area of the crane.

The method of analysis is to divide the building by one-span length in both the X and Y directions and by single floor heights so that the building is composed of several adjacent hexahedrons. To simplify the calculation to the worst case assuming that the loads within a single hexahedron are to be lifted at the far edge of it.

Constraints

1. To minimize the boom length of strut jib cranes, the location of the crane is adjusted in the Y direction in 1 m stages Y_i until it reaches the limit of the site boundary L_y. A formula for this constraint is shown by:

$$Y_i \leqq L_Y \tag{3}$$

2. The working range of crane type i must be equal to or greater than Y_i. A formula for this constraint is shown by:

$$Y_i \leqq R_i \tag{4}$$

3. Similarly, the constraint of lifting capacity can be shown by:

$$W_{y,j} \leqq W_{Yi} \tag{5}$$

4. The constraint of service-height can be shown by:

$$\frac{H_j - h_i}{Y_i - D} < \frac{L_{Bi}{}^2 - Y_i^2)^{1/2}}{Y_i} \tag{6}$$

For strut jib cranes where there is no service height provided by a mast h_i can be set to 0. The constraint is then one of the particular cranes' length of boom.

A model for the selection of a fixed base tower crane

The initial question, because of the limitation of the cranes working radius from a fixed point, is whether one crane is sufficient to cover the whole of the building area. This makes the decision flow chart (Fig. 1) more complex than that for the mobile crane, as the location and selection of multiple cranes must be considered.

The following definitions will be used in this section

(X,Y) = crane set up location
$X = 1, 2 \ldots A$
$Y = 1, 2 \ldots B$

where A is the number of spans in axis X direction and B is the number of spans in axis X direction + 1.

(x, y) = load lifting location on x–y plane
$x = 1, 2 \ldots A$
$y = 1, 2 \ldots B-1$
i = fixed base tower crane type number
$i = 1, 2 \ldots N$

where N is the number of different crane types.

C_i = hire cost/day for crane type i
$x_{i,\,(X,Y)} = 1$ or 0

where 1 is the crane type i set up at location (X,Y) and 0 = otherwise.

R_i = maximum working radius of crane type i
J = floor number
$j = 1, 2 \ldots m$

where m is the number of floors.

$W_{(x,y),j}$ = maximum lifting load of floor j at location (x, y)
$S_{(x,y),\,(X,Y)}$ = horizontal distance from location (X, Y) to (x, y)
$W_{i,S\,(x,y),\,(X,Y)}$ = maximum lifting capacity of crane type i at $S_{(x,y),\,(X,Y)}$ range
$a_{(X,Y),i,(x,y)} = 1$ or 0

where 1 is the working range and lifting capacity of crane type i at location (X, Y) to satisfy the condition of lifting the load at location (x, y). Namely, Equations 7 and 8 are satisfied,

$$R_i \geqq S_{(x,y),\,(X,Y)} \tag{7}$$

$$W_{1,S(x,y),\,(X,Y)} \geqq W_{(x,y),j} \qquad j = 1, 2 \ldots m \tag{8}$$

and 0 = otherwise. The expression $a_{(X,Y),i,(x,y)}$ is termed a covering matrix.

The model of the construction site and the building with a fixed base tower crane

The model of the construction site and building is shown in Fig. 3, which, for this example, is identical to that used in Fig. 2.

For ease of calculation, where cranes are set up adjacent to the building, they will be located within one span from the building with the crane always set up at the centre of each mesh.

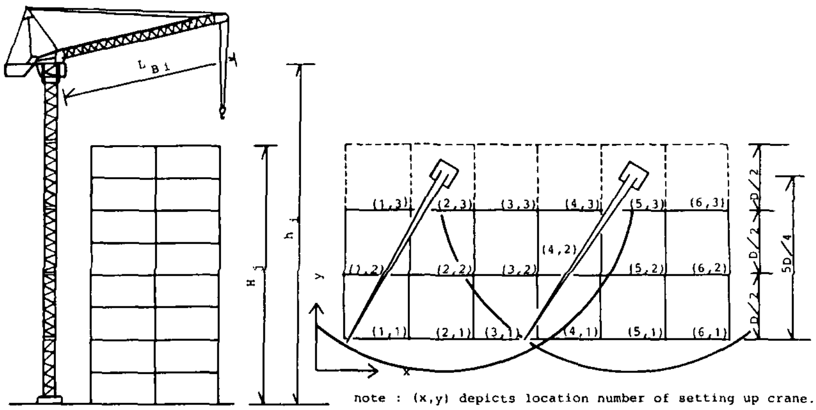


Fig. 3. Construction project model of site and static based tower crane.

Objective function

Since the hire cost of the crane combination per day is defined as F, the objective function can be defined as:

$$\text{minimize } F = \sum_{i=1}^{N} \sum_{X=1}^{A} \sum_{Y=1}^{B} C_1 \cdot x_{i,\,(X,Y)} \tag{9}$$

Constraints

1. Location (x, y) must be covered by one or more cranes. A formula for this constraint is shown by:

$$\sum_{i=1}^{N} \sum_{X=1}^{A} \sum_{Y=1}^{B} a_{(X,Y),i,(x,y)}\, x_{i,(X,Y)} \geqq 1 \qquad x=1,2\ldots A;\; y=1,2\ldots B-1 \tag{10}$$

2. Two tower cranes can not be set up at the same location. A formula for this constraint is shown by:

$$\sum_{i=1}^{N} x_{i,(X,Y)} \leqq 1 \qquad X=1,2\ldots A;\; Y=1,2\ldots B \tag{11}$$

Other possible constraints are as follows:

3. For example, the tower crane is not set up at location (X, Y)

$$\sum_{i=1}^{N} x_{i,(X,Y)} \leqq 0 \tag{12}$$

4. For example, the location (x, y) is covered by T numbers of cranes.

$$\sum_{i=1}^{N} \sum_{X=1}^{A} \sum_{Y=1}^{B} a_{(X,Y),i,(x,y)} x_{i,(X,Y)} \geqq T \tag{13}$$

Obtaining the solution which simultaneously satisfies the conditions of Equations 10 and 11 and which minimizes the condition in the Equation 9 means that the buildings can be constructed with one or more fixed base tower cranes and that the most suitable combination of them can be calculated. Conversely, obtaining a solution which does not satisfy the equations means that the building cannot be constructed with the particular combination of tower cranes. The value of const (I, j) for the fixed base tower crane is therefore:

$$\text{const } (I, j) = 1 \text{ or } 0$$

where 1 is the most suitable crane combination and 0 = otherwise; using the definitions

$$j = 1, 2 \ldots m$$
$$I = n + 1$$

where n is the number of different mobile crane types and I is the most suitable combination of the tower cranes.

The minimum crane cost calculation

Objective

In calculating the problem the objective is to find the path which minimizes the sum of values for each combination in passing from the first to floor m. In the example which follows there would be 3×10^{18} paths to calculate. In practice this is an impossible number of evaluations to make but dynamic programming techniques enable this to become manageable. A computer program has been written to undertake the calculation.

The following definitions will be used in the calculation

C_i = hire cost/day for crane type i
$d_{i,j}$ = working day for floor j crane type i
$t_{i,j}$ = total hire cost for floor j by crane type i

where $t_{i,j} = C_i \cdot d_{i,j}$

D_i = dismantling cost for crane type i
E_k = assembly cost for crane type k
$Z_{k,j}$ = minimum crane cost for floor 1 to floor j, in the case of floor j constructed with crane type k (not including dismantling cost for crane type k)

When floor $(j-1)$ is constructed with crane type i and floor j with crane type k,

$g_{i,k} = 1$ or 0,
$0 = i$ equal to k
$1 =$ otherwise
$i, k =$ crane type number of mobile crane and fixed base tower crane.
$i, k = 1, 2 \ldots n, n+1$
$n =$ number of different mobile crane types
$n+1 =$ most suitable fixed base tower crane combination
$j =$ floor number
$j = 1, 2 \ldots m$
$m =$ number of floors

Create dynamic programming model

In order to demonstrate the model, a hypothetical construction project has been devised as shown in Fig. 4.

To show the possible effect of the first choice of crane being unsuitable for all floors, the assumption is made that floor j will be constructed with crane type k. If floor $(j-1)$ is constructed with crane type k, there will be no dismantling cost needed at floor j. If floor $(j-1)$ is constructed with a different crane, type i, then the dismantling cost of crane type i and assembly cost of crane type k needed at floor j, must be added to the hire cost of crane i.

The above procedure enables the dynamic programming problem to be defined as an optimal locus problem. Thus, the following functional equations can be defined.

$$Z_{k,j} = \min_i \left[Z_{i,j-1} + t_{k,j} + (D_i + E_k)\, g_{i,k} \right] \qquad j = 2, 3 \ldots m$$

where

$$Z_{k,1} = t_{k,1} + E_k \qquad k = 1, 2 \ldots n+1$$

Finally the minimum cost is calculated as follows:

$$Z = \min_k Z_{k,m} + D_k \qquad k = 1, 2 \ldots n+1$$

The decision flow of this stage is shown in Fig. 1d.

Examination of the model

To demonstrate the capabilities of this approach an example analysis has been prepared using the input data shown in Table 2. Data for twenty types of cranes used to evaluate the model are shown in Table 1. Two sizes of construction projects have been tested assuming that the number of spans in the X axis are equal to 10, and that the maximum loads to be lifted are equal to 5, 3 or 1 tons.

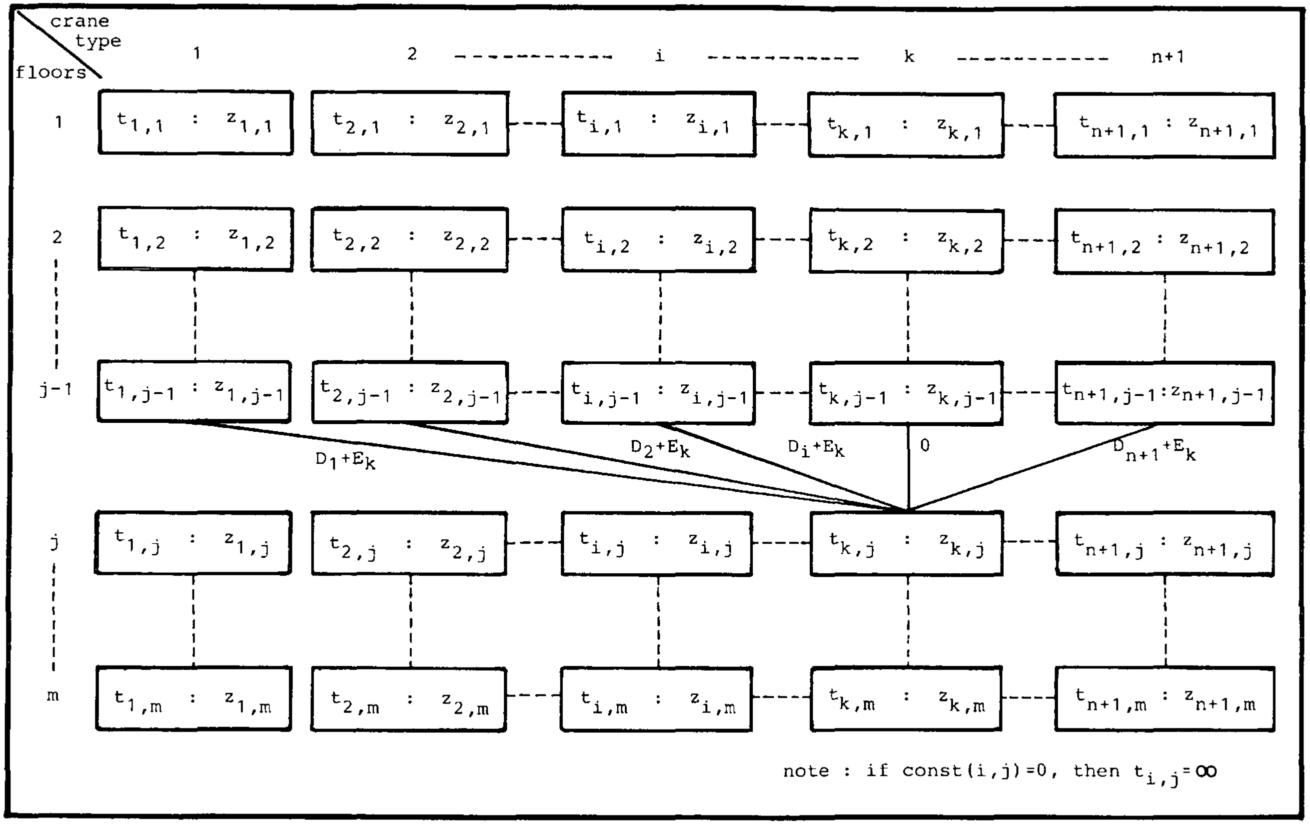


Fig. 4. Optimal locus model of DP.

Table 2. Input data.

Item	Contents	Examples
Crane data	Lifting capacity, working range, height of tower, length of boom, hire-cost, assembling cost, demolishing cost	Refer to Table 1
Duration	Duration for each floor	10 days same
Outline of construction project	Axis X; number of spans, span length	10, 6
	Axis Y; number of spans, span length	2, 6
	Number of floors, floor height	15, 3
	Area maximum lifting load for each floor	all areas = 5, 3 or 1 (e.g. $[(1.1)/1F]=1$)
	Site width in axis Y	30
Constraints	Inside of building site?	No
	Maximum numbers of available static based tower crane	
	Areas where crane can not be set up	No
	Areas where two or more cranes are needed	No

Output

The example of the output from the evaluation is shown in Fig. 5a–d. Fig. 5b shows the most suitable solution of Step 2. It means that if the building is constructed with the fixed base tower cranes, the most suitable combination is two cranes, crane type 17, and they are located at hexahedrons (1,3) and (7,3). Fig. 5a shows the detailed steps of the examination of each permutation and shows the covering matrix, the setting area of the tower crane and the condition of Equations 10–13. The lower part of Fig. 5a shows the value $x_{i,(X,Y)}$, that is, whether tower crane type i is set up at location (X, Y) or not. The upper part of Fig. 5a shows the covering matrix, $a_{(X,Y),i,(x,y)}$, and the value equal to 0 is shown as a blank for clarity. The two columns on the right-hand side of the matrix shows the value of Equations 10–13. The lines in Fig. 5a show the derivation of the solution in Fig. 5b, that is, two fixed base tower cranes set up at locations (1,3) and (7,3) can provide 100% lifting cover over the plan area. For example, the load lifting location (5,1) is covered by the crane set up at (7,3), and load lifting location (3,2) is covered by the cranes set up at (1,3) and (7,3).

Fig. 5c shows the optimum cranage solution. Firstly, floor 1 will be constructed with truck crane type 1. Secondly, floors 2 and 3 will be constructed with crawler crane type 7. Thirdly, floors 4 to 6 will be constructed with crane type 8; floors 7 to 14 with crane type 12; floors 14 and 15 with crane type 14. The above solution is obtained using Step 3, and the results are shown in Fig. 5d. In Fig. 5d the * expresses that floor j cannot be constructed with crane type i, i.e. the result of Step 2. At the point not marked *, two values are shown. The first value shows the crane type number which constructed floor $(j-1)$. If floor j is constructed with crane type i, it is the best crane type number to construct floor $(j-1)$ for the purpose of minimizing the crane cost.

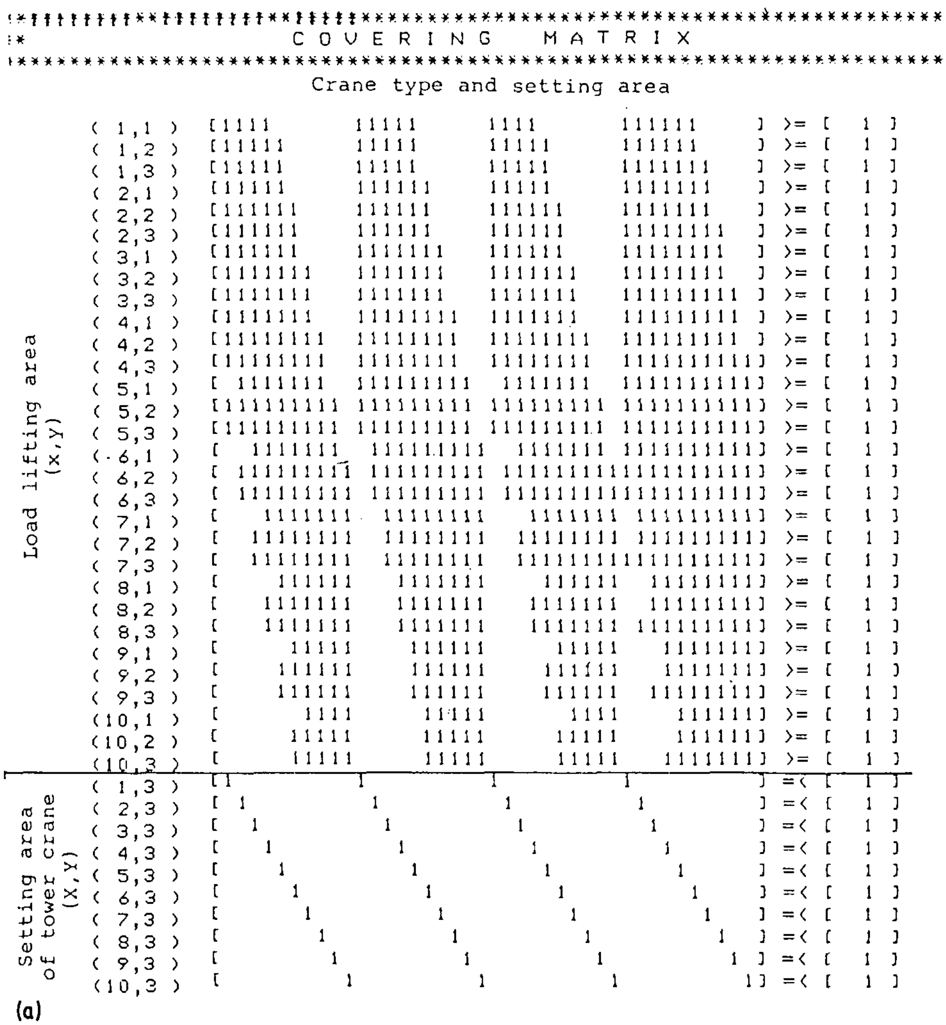


Fig. 5. (a) Covering matrix. (b) Most suitable solution of Step 2. (c) Most suitable solution of Step 3. (d) Crane cost calculation.

The second value represents the minimum crane cost to floor j when j is constructed with crane type i.

If floor 7 is constructed using crane type 12, constructing floor 6 with crane type 8 would be the best way to minimize the crane cost. The value is the sum of the cost to floor 6 (3050 units) plus the dismantling cost of crane type 8 (30 units), the assembly cost of crane type 12 (100 units) and the hire cost of crane type 12 for constructing floor 7 (80×10 days $= 800$ units). Thus, the total crane cost for this combination can be calculated by

```
COMBINATION OF STATIC BASE TOWER CRANES =   2

  CRANE NUMBER = 17 LOCATION (  1,   3 )

  CRANE NUMBER = 17 LOCATION (  7,   3 )
```

(b)

```
*** MINIMUM COST OF CRANE DEPOSITION =  1104
    --- CRANE DEPOSITION PLAN ---
         15 F --- CRANE NO. 14
         14 F --- CRANE NO. 14
         13 F --- CRANE NO. 12
         12 F --- CRANE NO. 12
         11 F --- CRANE NO. 12
         10 F --- CRANE NO. 12
          9 F --- CRANE NO. 12
          8 F --- CRANE NO. 12
          7 F --- CRANE NO. 12
          6 F --- CRANE NO.  8
          5 F --- CRANE NO.  8
          4 F --- CRANE NO.  8
          3 F --- CRANE NO.  7
          2 F --- CRANE NO.  7
          1 F --- CRANE NO.  1
```

(c)

Fig. 5. Continued.

$30*10+60+40*10*2+30+60+60*10*3+30+100+80*10*7+60+120+100*10*2+80$ as 11 040 units (1 unit = 1000 yen).

Results

The results of using the modelling technique for the example discussed are shown in Table 3. The last column in Table 3 is the calculation for using the same crane from the beginning of the project to construct all floors, the typical solution on most sites. The crane cost is calculated as the total of the assembly and dismantling cost of the crane for the full height, plus the hire cost which, for the worked example above, is crane type 14. The total cost can therefore be calculated by $120+80+100*10*15$ as 15 200 units.

Conclusions

The above is a simple model using management science techniques. The results, however, allow new ways of calculating the least cost crane option. The applicability of this model could be as follows:

1. Even for the same floor plan and lifting requirements, the least cost crane option may change at various floors in the project.

C R A N E   C O S T

	NO.1	NO.2	NO.3	NO.4	NO.5	NO.6	NO.7	NO.8	NO.9	NO.10	NO.11	NO.12	NO.13	NO.14	NO.15	NO.16	NO.17
COST TO 1 F	1- 30	2- 50	3- 60	4- 92	5- 154	6- 214	7- 46	8- 66	9- 86	10- 148	11- 228	12- 90	13- 100	14- 112	15- 200	16- 280	17- 128
COST TO 2 F	*- *	1- 80	1- 90	1- 122	1- 184	1- 244	1- 76	1- 96	1- 116	1- 178	1- 258	1- 120	1- 130	1- 142	1- 230	1- 310	1- 158
COST TO 3 F	*- *	*- *	7- 139	7- 171	7- 233	7- 293	7- 116	7- 145	7- 165	7- 227	7- 307	7- 169	7- 179	7- 191	7- 279	7- 359	7- 207
COST TO 4 F	*- *	*- *	7- 179	7- 211	7- 273	7- 333	*- *	7- 185	7- 205	7- 267	7- 347	7- 209	7- 219	7- 231	7- 319	7- 399	7- 247
COST TO 5 F	*- *	*- *	*- *	3- 271	3- 333	3- 393	*- *	8- 245	3- 265	3- 327	3- 407	3- 269	3- 279	3- 291	3- 379	3- 459	3- 307
COST TO 6 F	*- *	*- *	*- *	8- 340	8- 402	8- 462	*- *	8- 305	8- 334	8- 396	8- 476	8- 338	8- 348	8- 360	8- 448	8- 528	8- 376
COST TO 7 F	*- *	*- *	*- *	8- 400	8- 462	8- 522	*- *	*- *	8- 394	8- 456	8- 536	8- 398	8- 408	8- 420	8- 508	8- 588	8- 436
COST TO 8 F	*- *	*- *	*- *	9- 489	9- 551	9- 611	*- *	*- *	9- 474	9- 545	9- 625	12- 478	9- 497	9- 509	9- 597	9- 677	17- 516
COST TO 9 F	*- *	*- *	*- *	*- *	9- 631	9- 691	*- *	*- *	*- *	9- 625	9- 705	12- 558	9- 577	9- 589	9- 677	9- 757	17- 596
COST TO 10 F	*- *	*- *	*- *	*- *	12- 718	12- 778	*- *	*- *	*- *	*- *	12- 792	12- 638	12- 664	12- 676	12- 764	12- 844	17- 676
COST TO 11 F	*- *	*- *	*- *	*- *	*- *	12- 858	*- *	*- *	*- *	*- *	12- 872	12- 718	12- 744	12- 756	12- 844	12- 924	17- 756
COST TO 12 F	*- *	*- *	*- *	*- *	*- *	12- 938	*- *	*- *	*- *	*- *	12- 952	12- 798	12- 824	12- 836	12- 924	12-1004	17- 836
COST TO 13 F	*- *	*- *	*- *	*- *	*- *	12-1018	*- *	*- *	*- *	*- *	12-1032	12- 878	12- 904	12- 916	12-1004	12-1084	17- 916
COST TO 14 F	*- *	*- *	*- *	*- *	*- *	12-1098	*- *	*- *	*- *	*- *	12-1112	*- *	12- 984	12- 996	12-1084	12-1164	17- 996
COST TO 15 F	*- *	*- *	*- *	*- *	*- *	13-1206	*- *	*- *	*- *	*- *	13-1223	*- *	*- *	14-1104	*- *	13-1310	17-1108

(d)

Fig. 5. Continued.

Table 3. Model calculation.

NSX	SLX (m)	NSY	SLY (m)	Floors	MLL (ton)	DEF (days	MSC Floor	MSC Crane number	Cost (× Y1000)	CWD (× Y1000)
10	6	2	6	15	5	10	1–13	12		
					3	10	14–15	14	12 760	15 200
							1–2	3		
					2	10	3–13	12	12 360	15 200
							14–15	14		
							1	1		
							2–3	7		
					1	10	4–6	8	11 040	15 200
							7–13	12		
							14–15	14		
10	6	2	6	30			1–13	12		
					5	10	14–16	14	37 120	48 960
							17–30	19, 19		
							1–13	12		
					3	10	14–16	14	32 440	39 480
							17–30	20		
							1–2	3		
					2	10	3–13	12	26 260	27 800
							14–30	17, 18		
							1	1		
					1	10	2–3	7	23 080	24 800
							4–6	8		
							7–30	17, 17		

Note: NSX = number of spans in axis x; SLX = span length in axis x
NSY = number of spans in axis y; SLY = span length in axis y
MLL = maximum lifting load; DEF = duration for each floor
MSC = most suitable crane; CWD = cost without optimization
Y = yen

2. Even for the same floor plan and number of floors, the least cost crane combination may be changed substantially by the different loads to be lifted.

3. The normal approach to crane selection assumes that the same cranes for the first floor are used through to the top floor and are set up at the very beginning of the project. However, the solution from this model shows that this is a less than optimal approach.

4. However, whilst it may be ideal to vary the type and number of cranes during the construction, the effect of assembling and dismantling several cranes must be taken into account. Also such effects as delays to the construction, the provision of a clear site area for assembly of the cranes and the area needed for attendant cranes, particularly where large volumes of materials are stacked for the continuing construction must be considered.

5. The model does show that it is possibly more economical at first to use the crane with the lower hire cost, and replace it once it reaches its limitation of capability and capacity.

Further development of the model

Since this model is a simple one and based on several limiting assumptions, further development is required to enable the model to predict cost in a more realistic situation. Such developments could be as follows to avoid the assumptions which have been made above.

1. The assumption made in the model is that the working duration of each floor would not be affected by the lifting capability of any crane. Further consideration should be made which would include the effect on the working duration.
2. The assumption made in the model is that the model presumed an idealized building without taking account of the resource limits on the availability of the cranes. Further developments should enable complex building sites to be evaluated.

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