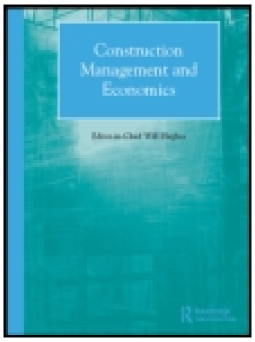

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A procedure for quantitatively evaluating site layout alternatives

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Construction site layout decisions affect the effort involved in materials handling, an activity which occupies a substantial portion of working time. Much computer software has been developed enabling construction managers to plan and visualize the layout of a construction site, but at present the lack of an accepted practical technique for evaluating the efficiency of a chosen site layout makes it difficult to choose objectively between possibilities, in the search for a better layout design. The research described in this paper explores the practicability of an evaluation procedure intended to help improve this situation, and effectively describes the use of a quantitative material flow network model as the basis for evaluating the efficiency of a given site layout option. The evaluation measure, 'total material flow time', is calculated as part of an evaluation procedure. A site trial of the procedure is described, and its necessary development into a computer assisted procedure is discussed.

Keywords: Site layout, quantitative evaluation, material flow

Site space planning evaluation

Space planning typically results in a layout which indicates the positions of storage areas, access locations, temporary facilities and key items of plant in relation to the locations of the permanent facilities under construction (Riley and Tommelein, 1996). Plant must be located and space provided in which it can move and manoeuvre. Labour needs room to work. Materials must be stored until needed and transportation routes provided for all materials from the site entrances to their final destinations in the permanent works, often via various staging areas including laydown and assembly areas. Research described in the next section has shown that, typically, marshalling materials and plant occupies more than a third of all working time. Site space planning must consider the sizes of and constraints on spaces needed by activities at specific times, and aims to optimize the efficiency of construction operations, usually to minimize time and/or cost spent in moving materials and avoiding interference between construction operations. In spite of the potential handling efficiency gains, routine objective evaluations of site layout efficiency remain uncommon in practice because so much detailed analysis is required. In fact, site usage decisions rely mainly on the judgement of experienced construction managers.

Computer graphics, in the meantime, have developed quickly, and computer-aided software is available to assist construction managers to lay out and visualize a construction site and to better communicate layout intentions to all concerned. However, the lack of a layout evaluation technique which works in sufficient detail to be reasonably accurate prevents the computer's power being used to assist in the search for good solutions. Thus it is highly desirable to find a method for accurately evaluating a site layout plan, a method which can ultimately be assisted by computer processing and visualization software.

An assessment of the practicability and potential of a proposed site evaluation procedure and its first trial, manually processed at this stage, on a small multistorey building site was the objective of the research reported here.

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Relevant research

Materials management for enhanced productivity

Marshalling tools, materials and plant is a necessary continuing component of production activity which has been shown by past research to occupy a large amount of productive working time, very broadly of the order of one third and more (Strandell, 1976; Neil and Lee, 1984; O'Brien, 1989). Hanna and Heale (1994) concluded that material management factors have a 'severe' impact on labour productivity. Thomas and Napolitan (1995) stated that materials management is an important factor affecting construction efficiency. On power plant construction sites Borcherding and Sebastian (1980) found that 27.7% of craft worker time was idle or non-productive due to a lack of materials and tools at the right time. Burkhart and Pault (1985) pointed out that materials were not stored closely enough to the work area. O'Brien (1989) found that site workers spent 42% of their time on materials handling and preparatory operations.

In general, it can be concluded that the achievement of efficient materials management is a very important objective, and that a site layout design which reduces material travel time will enhance construction productivity.

To confirm that the broad conclusions above apply also to multistorey building sites in Hong Kong, two buildings under construction in 1997 were studied for two and a half months each. Each of the two sites, A and B, contained a single high rise building. Table 1 shows some of the results. The value of $P/(P+M)$ of about 0.4 means that M at 0.6 was about 50% greater than the direct productive work time. Since M occupied 38.5% of total time, idle time and other non-productive uses of time totalled about 35% of the whole time available.

Site layout research

Experience based guidelines to good site layouts are provided by Neil (1980), Popescu (1981) and Rad (1982). Rad and James (1983) provide a step-by-step approach for laying out a site. Heap (1987) describes general considerations for site layouts and Handa and Lang (1989) provide a checklist for judging construction site efficiency. This type of research, which attempts to capture experience, may lead to expert systems as tools to assist in obtaining a good layout. A graphical research model by Tommelein *et al.* (1991, 1992b), for example, introduces a knowledge-based system to automatically generate layouts using typical 'rules'.

Many other researchers have studied single-facility location optimization problems with evaluation criteria based on e.g. minimizing time, cost or distance. Gates and Scarpa (1978), for example, provided a method for optimizing the location of haul roads, and Rodriguez-Ramos and Francis (1983) studied a tower crane location problem. However, practical sites are multi-facility problems, and Rodriguez-Ramos (1982) in addressing this proposed total transportation cost as an evaluation measure. Though his cost evaluation model is complex he showed that thorough and realistic analyses can lead to better solutions.

Computer graphics modelling has been used relatively recently to aid site visualization and perhaps help identify potential interference problems. Yip and Anson (1996), for example, produced a 2D layout planning and updating system to represent temporary and permanent facilities and their construction status on site. The system proved to be operationally acceptable on a simple two-tier road project, and was used to communicate site use intentions via copies of the screen layouts on which interactive planning had taken place. Building on that work, Zhang (1996) developed a 3D visual simulation model for multi-storey buildings specifically with site use planning as the objective. 4D models are also being studied which integrate 3D with time via a construction schedule, e.g. Williams (1996). In general, because computer visualization models are now so realistic, much current research is exploring how to integrate graphics with other site management subsystems, such as project scheduling and materials ordering. Given a plan evaluation capability, site plan evaluation would be another management function worth assisting by linking to visualization graphics.

Table 1 The results from site studies A and B in 1997

Parameter[a]	Mean value		Range over the study period	
	A	B	A	B
$P/(P+M)$	0.42	0.40	0.34–0.51	0.25–0.55
M/T	0.38	0.39	0.27–0.47	0.26–0.52
Sp	0.45	0.51	0.35–0.60	0.47–0.56

[a] P is the direct productive work time, M is the work time moving material, T is the total worker time (i.e. $P + M$ + idle time + travelling time), and Sp is the proportion of space used for material handling to total space available.

The evaluation study

At present, although computers can display increasingly sophisticated and realistic looking site layouts, the evaluation of how good those site layout plans are, as stated above, is left to visual inspection and the judgement of the planner. A formal layout evaluation procedure for routine site use, which can be used to evaluate any option and can be integrated with visualization modelling, remains to be developed.

The MFT network

Research has indicated very clearly that if the time needed for marshalling materials can be decreased then productivity will increase. Based on this principle, 'material_flow time' (MFT) was selected as the evaluation criterion for the research presented here. Even though material flow cost would theoretically be more appropriate, MFT is much simpler to estimate and likely to correlate well with cost. To include cost related data would complicate the evaluation enormously, affecting practicality and bring-up questions of what costs to include. An MFT based layout evaluation procedure was therefore decided upon and tested with a site trial.

The material flow process

Material flow is the process of moving materials from the site entrance(s) through a set of function areas to the final installation areas. The flows between function areas can be modelled by a network, as illustrated in Figure 1 after Tommelein (1994). Six types of function area have been defined: laydown areas, staging areas, assembly areas, installation areas, wastes areas and site entrances. Roads differ in nature from these function areas, but they play an important role in the material flow processes, and also must be identified.

A 'laydown area' is allocated for long term use and usually each main material has its own laydown area. Examples include steel, large panel formwork, and precast facades. Materials which are needed occasionally, or even frequently if their volumes are small, may share a common laydown area. A 'staging area' is for short term temporary storage. Some materials are assembled or fabricated before being installed in their permanent places, and 'assembly areas' are allocated for this purpose. An 'installation area' is the working area needed when materials are being placed where they finally remain. 'Wastes areas' are also needed. 'Site entrances' connect to the outside road system. 'Roads' refer to the internal transportation routes on the site, whether used by vehicles or solely by foot traffic, and are divided into sections as appropriate. A 'non-function area' includes, for example, site offices, worker changing rooms, and tools storage. An 'unused area' is simply not used and may be unusable. Some unusable areas may be made usable as a result of further work, but the additional cost involved has to be allowed for. Once delivered, materials are usually placed in a laydown area, assembly area or staging area, and seldom are taken to the installation area directly.

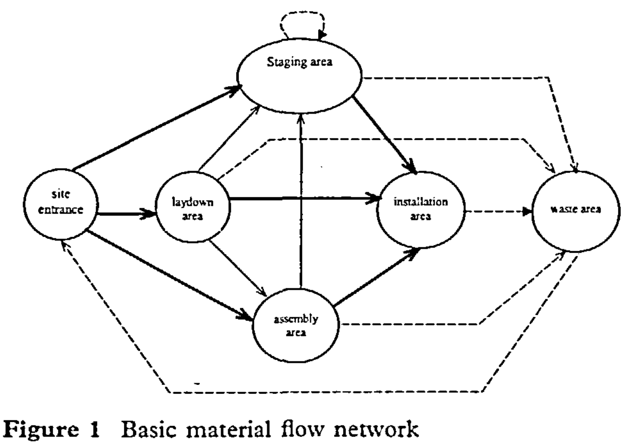

Figure 1 Basic material flow network

Constructing an MFT network

The proposed MFT implementation procedure starts by dividing the construction site area, on a general site plan, into a set of n numbered function areas. Planned material flows between these function areas are indicated by arrows, and thence a material flow network diagram is drawn. Each arrow represents a material flow element (MFE) of the network connecting two function areas i and j, and is annotated with flow information including quantity of the material, distance to be moved, moving speed, and how many times the operation will occur. The total material flow activity associated with an MFE is a set of individual repetitive material flow operations (MFOs). Since any complex flow network can be constructed as a set of MFEs, where each MFE represents a flow activity for a specific material, it remains to estimate the time needed for an MFO and, hence, to compute the whole material flow time for the MFE concerned. The MFT value is simply then the sum total for all MFEs.

MFT calculation

Figure 2 illustrates the structure of the MFE flow data for a particular material in the form appended to each arrow in the field trial described below. Rows 1, 2 and 6 contain basic data supplied by the planner. MC is a code number representing the handling category (see below) into which the material falls, M is the material type code number and TT the code number for the transportation 'tool'. Different transportation tools move items at different speeds, and a particular transportation tool may operate at different speeds with different materials and also with the way the materials are packaged. Row 2 is for flow route coordinates and row 6 gives the total material quantity Q for this activity. The normal convenient quantity which can be

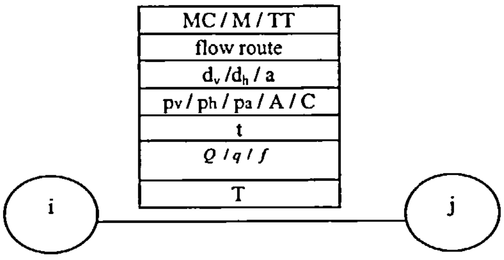

Figure 2 The standard MFE

moved in each MFO is denoted by q. The number f of moves is calculated from Q/q. d_v, d_h, and a in row 3 are the vertical and horizontal distances and any angular rotation involved in moving the material. These would be calculated automatically from rows 1 and 2 by a software-supported procedure linked to a 3D graphics site model.

In row 4, the *p*v, *p*h, and *p*a represent the vertical, horizontal and angular times for unit distances moved. The transportation tool loading up time is given by A and the unloading time by C. A software-supported system which accessed a database of typical movement speeds, and loading and unloading times would complete row 4 automatically.

In rows 5 and 7, t is the time taken by an MFO and T the total time for the whole material flow activity on that MFE. More formally, if a material flows from i to j, the MFO time is given by

$$t_{ij} = A_{ij} + (p_v \cdot d_v + p_h \cdot d_h + p_a \cdot a)_{ij} + C_{ij}$$

and the MFE time by

$$T_{ij} = f_{ij} \cdot t_{ij}$$

The total material flow time for the whole site is given by

$$MFT = \sum_{i=1}^{n} \sum_{j=1}^{n} T_{ij},$$

where n is the total number of function areas.

The trial evaluation procedure

The following proposed step-by-step procedure was adopted on the trial site.

Step 1. Draw site layout alternatives judged likely to be effective.
Step 2: Divide the site roads into numbered sections.
Step 3: Identify material categories, and supply the database with p, A and C values.
Step 4: Identify and number each function area. Delineate the function areas on the site layout plans and use coloured lines to represent material flows.
Step 5: Draw the material flow network diagram and compile the data as in Figure 2 for each MFE.
Step 6: Calculate the whole material flow time, MFT, by totalling for all MFEs.
Step 7: Repeat steps 2–6 for each site layout alternative.

An experiment on site

A site study was conducted for two and a half months to test the workability of the proposed evaluation procedure, to estimate the effort involved in using the model, to identify the information needed for the model to be usable, and to identify the shortcomings of the model and any necessary improvements. The project consisted of a single building and a pedestrian footbridge on a site which backed onto a slope on three sides, and had a road in front over which the footbridge passed, as illustrated in Figure 3. The building was a 21-storey small household block 63 m × 14 m on plan, approximately 60 m high and containing 240 domestic units in 20 upper floors. The external facades of the units were constructed in pre-cast concrete panels made off-site. The building had a shear wall structure, with large panel formwork for the construction of walls, and timber for slabs, on a six-day construction cycle.

The main building site was 105 m long × 35 m wide, with two entrances. A tower crane which could reach almost everywhere was located at the centre of the site. The site study was carried out during the early superstructure stages when a material hoist had not yet been erected. The building superstructure plan area occupies about 22.5% of the site area. The work followed the procedure described above, and the trial related to material movement calculations for the construction of the first ten floors.

Materials were divided into six categories for the site evaluation trial. The first category was loose material, which includes concrete, sands and aggregates. The second was packed material, such as scaffold tiles, cement, bricks and timber. The third was long elements such as steel bars and electrical conduit. The fourth was large vertically slung units, such as a pre-cast concrete façade, and the fifth was large panel formwork, which usually was not as heavy as the large vertically slung units and had different values for A, p and C. The last category was a large horizontally slung pre-cast slab. Each materials handling category, material name and transportation tool was given a shorthand identification number for convenience. For example a 'long element' was given the materials handling category code MC02; a 'mobile crane' was given the transportation tool code T07; and 'scaffolding' given the material code M004.

Values of p, A and C depend upon the various combinations of transportation tool and materials handling category. Table 2 is the database specially derived for the experimental evaluation, from prior studies on the trial site itself. It has been pointed out to us that if A and C are fixed values, very largely independent of the flow routes themselves, then it is necessary only to compare the flow times of alternative layouts. For practical purposes this simplification might often be satisfactory but, in general, different layouts can result in more or less moves for any material, in different move quantities (q), and in the use of different transportation tools. Any one, two, or three of these might apply.

Five site layout alternatives were proposed, A, B, C, D and E, and for each alternative the following were successively prepared:

- Site layout plan with coloured lines representing the flow of each material;
- Table of function areas and associated material quantities;
- Material flow network diagram with flow information and calculations.

The 5 alternatives probably identified all the practical possibilities on this site in fact. In general, however, in finding an optimum solution, feedback from the evaluations themselves should inform the process of selection of further alternatives.

Figure 3 is the site layout plan for alternative E, for which large panel formwork is allocated to areas 48, 49 and 15. (Areas such as 100, 101, 105, etc., are installation areas.) The four alternatives A, B, C, D used only half of the areas 48, 49, 15 for large panel formwork, but C and D also used 10 for this purpose with electrical conduit staging moved to 5 and 47, respectively. A and B differed in the way entrances were regulated between concrete truckmixers and other vehicles. The main purpose of Figure 3 is purely to enable the reader to get some feel for the nature of the experimental site.

Figure 4 is a numerical example of Figure 2, giving the actual figures in one of the boxes which appears on the full network diagram (not reproduced here). Row 2 of Figure 4 was not used for flow route coordinates in this manual trial because the researcher found it easier to work out the distances of row 3 directly. The '+' sign signifies a clockwise crane rotation.

Table 2 The database for the experiment

Value of p in seconds per unit distance moved[a]

	Loose materials			Packed materials			Long elements			Large panel		Scaffold and timber	Large vertical unit		
T.T.	R	L	H	R	L	H	R	L	H	R	L	L	R	L	H
Tower crane	0.34	1.17	–	0.36	1.23	–	0.36		–	0.47	1.29	3.33	0.91	2.29	–
Truck	–	–	4.55	—	–	–	–	–	3.00	–	–	–	–	–	–
Crane truck	–	–	–	–	–	2.00	–	–	–	–	–	–	–	–	1.86
Truck mixer	–	–	2.57	–	–	–	–	–	–	–	–	–	–	–	–
Manpower	–	–	0.78	–	–	–	–	–	1.00	–	–	–	–	–	–

Value of A in seconds

T.T.	Loose material	Packed material	Long elements	Large panel	Scaffold and timber	Large vertical
Tower crane	17.73	58.21	43.33	45.54	52.73	32.00
Truck	580.00	–	0.00	–	–	–
Crane truck	–	0.00	–	–	–	0.00
Truck mixer	0.00	–	–	–	–	–
Manpower	60.00	–	30.00	–	–	–

Value of C in seconds

T.T.	Loose material	Packed material	Long elements	Large panel	Scaffold and timber	Large vertical
Tower crane	176.82	70.36	56.67	93.75	43.18	291.00
Truck	92.50	–	1800.00	–	–	–
Crane truck	–	1000.00	–	–	–	650.00
Truck mixer	600[b]	–	–	–	–	–
Manpower	0.00	–	20.00	–	–	–

[a] R, rotate; L, lift, and H, horizontal movement.
[b] unloading time plus slump test.

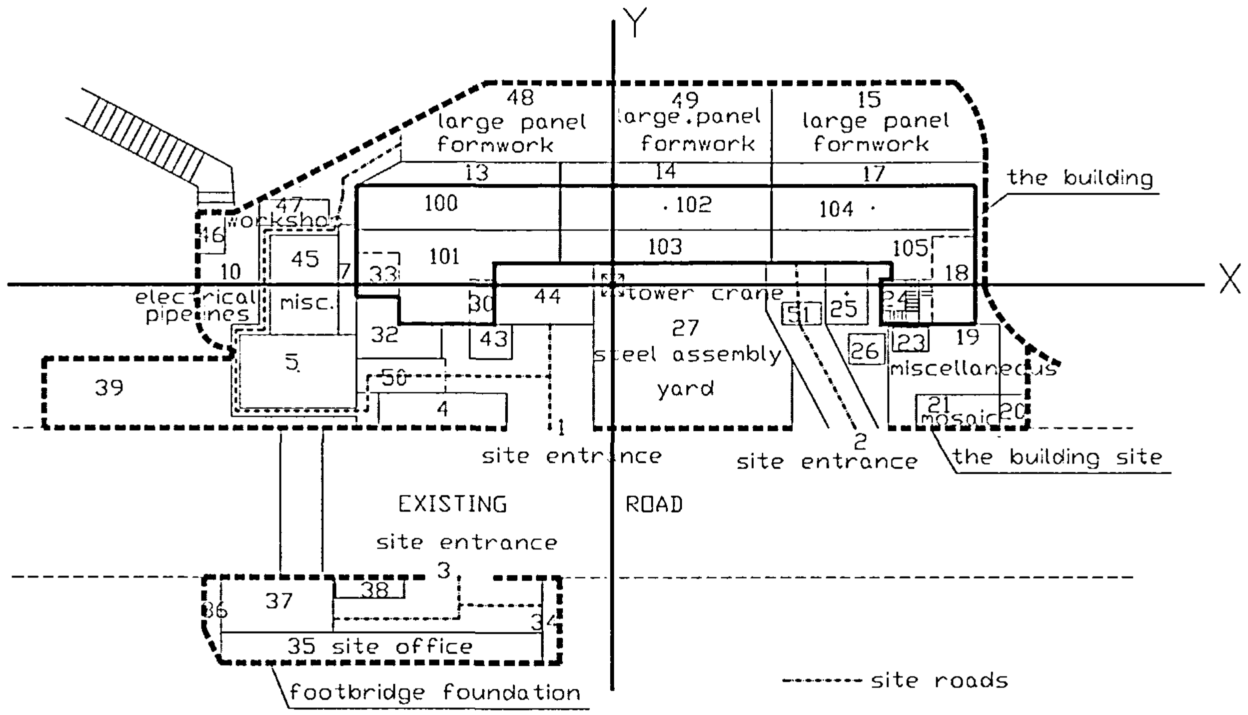

Figure 3 Site layout plan for alternative E

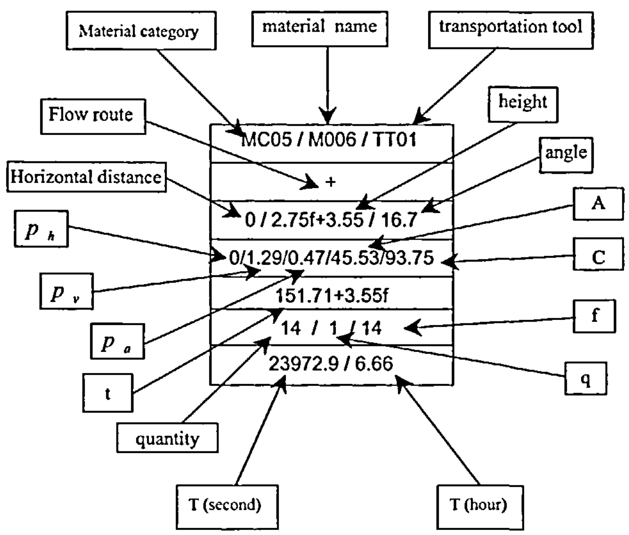

Figure 4 An MFE data example

It should be added that, in addition to the main *ij* flows, reverse *ji* flows sometimes exist, and also some cycling within a function area, *ii* flows. The model formulation (equation 1) allows for such flows to be included. It should also be noted that in the trial any *ij* flow related to one material only. It has been pointed out to us that equation 1 could be generalized to allow any function area *ij* set to be used for more than one type of material flow. The need did not arise on the trial site, but it is easy to imagine situations on very large sites where this might be useful.

The calculations were performed by hand for this pilot study, directly on the network diagram in a cumulative manner until the total material flow time value *T* appeared at the final node, in a manner reminiscent of the forward pass on a CPM network. The final value for *T* is shown in the box at the end node. Clearly the procedure is a simple one and could be set up for computer calculation.

Experimental results

The calculated total material flow times are shown in Table 3. Alternative E is the best, but there is very little difference between all 5 alternatives. γ is the ratio of the MFT value for the ten floors of construction concerned to the total time available for those floors. It is of no practical importance at this stage, but if site evaluations of this type do become routine then this is a parameter useful for comparing the performance of like sites and providing benchmarks. Table 3 also shows that moving itself, on this site, represents only about 20% of the total time, the remainder being represented by the loading and unloading of the transportation tools. On this site, the total loading and unloading times are affected very little by the site layouts adopted, but there are differences nevertheless because transportation tools were not exactly the same for all materials for all layouts. In general, for larger more complex sites, it cannot be assumed that ΣA and ΣC would remain quite so constant for different layouts. The table also highlights the importance to productivity of speed of loading and unloading.

This construction site was able to be described for material flow purposes using the six function area types defined above plus roads. The proposed procedure also proved workable, but an overall time of about three weeks was needed to produce these thorough estimates of material flow times.

The effort involved included:

- 18 hours for collection of the p, A and C values;
- 29 hours for compilation of material quantities, material category identification, function area identification;
- 19 hours for drawing the material flow network diagram with flow information for the five alternatives;
- 22 hours for drawing all five alternative layout plans using AutoCAD. The author was not familiar with AutoCAD at the start, and this time could be reduced.
- Because this was the first use of the model, an additional 20 hours was used for modification and adjustment;
- 5 hours for calculation of the whole material flow time for all of the five cases.

In general, for this small site of five alternatives, a total time of 93 hours (about two and a half weeks) was needed (not including the additional 20 hours of 'learning' time for modification and adjustment).

Discussion

Table 3 suggests alternative E is the best. Although the site manager would like to have used E, he had not done so because two different final finished levels (38.00 and 40.20) across areas 49, 15 and 48 were required. If the whole area had been levelled at 38.00m to facilitate E, time consuming and costly backfill up to 40.20, and compaction would then have been required when the superstructure was finished. This illustrates that some expert judgement is needed in deciding what quantitative analyses should be performed and in interpreting those that have been made. This does not cast doubt on the value of quantitative information but reminds us that a quantitative model such as MFT provides only part of the information needed in general. If E had produced a value much lower than 374.6, for example, it might have been judged worth the extra excavation and backfill costs.

Table 3 The 5 alternatives compared

Alternative	MFT (hours)	MFT components (hours) ΣA	moving	ΣC	γ	Merit order
A	381.3	54.4	75.5	251.4	79.4%	3
B	388.0	54.4	82.2	251.4	80.8%	5
C	385.3	54.4	79.9	251.0	80.3%	4
D	380.3	51.1	78.7	250.5	79.2%	2
E	374.6	51.4	74.2	249.0	78.0%	1

It would be possible to save much of the 29 hours spent in the collection of material quantities and identification of function areas and material category and much of the 18 hours spent on collecting p, A and C values plus the 19 hours for drawing the material flow network diagram if a computer automatically looked up a suitable project data base of dimensions, and provided some of the data in the boxes and drew the network. In addition, the 22 hours of AutoCAD drawing could be reduced to approximately 8 hours for these site layout alternatives by a practised AutoCAD user. A fully computer assisted approach would have needed only about one week of total effort.

With computer assistance and the availability of a good materials handling productivity database, one week of effort, or say two man weeks for a large site, ought not to be considered excessive because of the extensive time spent in materials handling. Even a small saving of only 5% might well be worth that degree of effort. Computer assistance developments and the database, however, must be available if site evaluations are to become routine.

The results for the five alternatives show there is little to choose between them on this small site, and it may be concluded that the effort was of no value to management (beyond providing reassurance), and therefore unnecessary from that point of view. On a larger site, however, significant differences between alternatives of up to 12% using the same MFT based procedure have been found. It is planned to report this separately in detail, confirming that the material flow evaluation effort is worth making.

The work requires discipline and arduous attention to detail. In these respects it is not unlike the work involved in planning and scheduling via critical path networks, first used manually on construction sites 35–40 years ago and now assisted by well known computer software packages. It is argued that similar computer assisted efforts to estimate material flow times should be developed so that site layout evaluation becomes a routine discipline. Such software, for maximum effectiveness, would access a materials handling productivity database and a 3D graphic model of the project and site for the necessary geometric data.

Materials handling productivity databases would be developed and kept updated if materials movement evaluation were ever to become routine. This would also enable MFT to be deliberately used as a research tool for studying both actually adopted and theoretical site layouts, to increase our understanding of the art, and possibly to define good site layout practice.

Conclusions

The site study has demonstrated the practicability of quantitatively evaluating a construction site layout in terms of the total time occupied for all main material flows, based on a network diagram of these flows. The nature of the necessary associated data has been obtained. The quantitative analysis of alternative site layouts is valuable information supporting site layout planning decisions.

On a small site, three man weeks of effort were required to analyse five alternatives using the manual MFT network approach. It is judged that this could be reduced to about one week with computer assistance and access to a research derived database of material handling productivity data. It is suggested that some such disciplined approach to the planning of a site layout should be adopted by the industry and become routine, since such a large part of the work on any site is involved in material movements. Software development work enabling as much computer assistance as possible is required to make this a practical reality. There is no reason why such software could not be developed and linked in with 3D modelling packages for maximum effectiveness.

Acknowledgements

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