Evaluating Construction Time Performance of Building Floor System Design at the (Early) Conceptual Design Stage

Arazi Bin IDRUS

Selangor University of Industry (UNISEL), Jalan Zirkon A 7/A, 40000 Shah
Alam, Selangor, Malaysia, araziidrus@hotmail.com

Abstract In building design, the basic system of structural elements such as floors is usually determined during the conceptual stage of the design process using the adaptive (or routine) method. In this method, a design is selected upon evaluating a number of possible options from a known database of solutions to suit a particular situation. However, due to the complexity of the problem, the evaluation and subsequent selection are often based on subjective judgment, past experience and familiarity, particularly whenever speed criterion is being considered. Any decision is then likely to be biased, and there is no guarantee that the choice will be optimum. This paper reports on the development of a more objective and systematic procedure in evaluating construction speeds of floor systems at the conceptual design stage. The procedure involves identification of construction activities associated with the floor system under consideration, measurement of the quantity of work for each activity derived using basic information regarding design of the building, determination of a productivity rate to suit the schedule, and selection of the appropriate level of resources. Based on this information, construction speed is quantified using a simple bar chart technique but in conjunction with a specially developed 'lead-in index' method of lead-in times estimation. Some validation of the procedure has been carried out and it has been found that the procedure is able to produce sufficiently accurate results. The procedure would thus allow a more well-informed and better choice of floor systems to be made at the early design stage.

Keywords: Adaptive design evaluation, building floor systems, construction times, bar charts

1. Introduction

Building design can be regarded as a complex reasoning process during which requirements are analyzed and solutions are evaluated against them. To understand fully the procedures involved, researchers find it convenient to divide building design into its various stages. Stages of building design that are widely used in practice are conceptual (or outline), preliminary (or intermediate or schematic) and detailed. The conceptual design stage is where overall concepts and ideas are formed and realisation of a solution to the design need begins to emerge. The preliminary stage of the design process further investigates the concept(s) formed in the conceptual stage to produce a definitive design layout. The detailed design stage specifies details of individual components so that the design can be ready for manufacture.

The conceptual stage places the greatest demands on the designer, since it is where the most important decisions are made and provides the most scope for improvement. The ability to influence cost is also greatest at this stage. The stage is typified by the *adaptive* (or *routine*) method of design i.e. the process of selecting a design from a known database of solutions or systems to suit a particular situation [1, 2]. Despite its importance, many decisions made at this stage are often based on judgment, rules of thumb, past experience and familiarity [3, 4]. In such a decision, an element of subjective bias is likely to occur [5], and there is no guarantee that the choice will be optimum [6, 3].

The basic system to be adopted for principal building structural elements such as floors, beams, columns and roofs is decided during the conceptual design stage using the adaptive method mentioned above. Under this method, a structural system is selected upon evaluating a number of possible options on their performance against a number of criteria. Among these are structural strength, cost, speed ('quantitative' criteria) and quality, buildability and familiarity ('qualitative' criteria). While design engineers have established reliable empirical rules and charts to assist them in evaluating strength of structural elements, and adequate methods in estimating their costs at the early design stage (e.g. area methods, elemental estimating, resource analysis), the assessment of their construction time performance is still very much based on their subjective judgment and past experience [7] and is therefore subject to the shortcomings described earlier. Among the elements, floor construction is the most time-consuming and costly activity particularly for a framed building, representing some 60%-80% of the total in both cost and time [8,9].

This paper reports on the development of an objective and systematic procedure for evaluating construction time performance (or 'speed') of building floor systems at the (early) conceptual design stage. In this study, 'floor system' is defined as a structural system consisting of both the structural floor slab and any beams supporting it. The study will focus on *concrete* or *concrete-based* floor systems since this is the main and most common material for floors. Among the widely used systems are precast hollowcores on cast-in-situ concrete beams (or 'in-situ beams' for short) (see Fig. 1 for illustration); semi-precast lattice girder planks on in-situ beams; precast solid planks on in-situ beams and in-situ flat slab on in-situ columns.

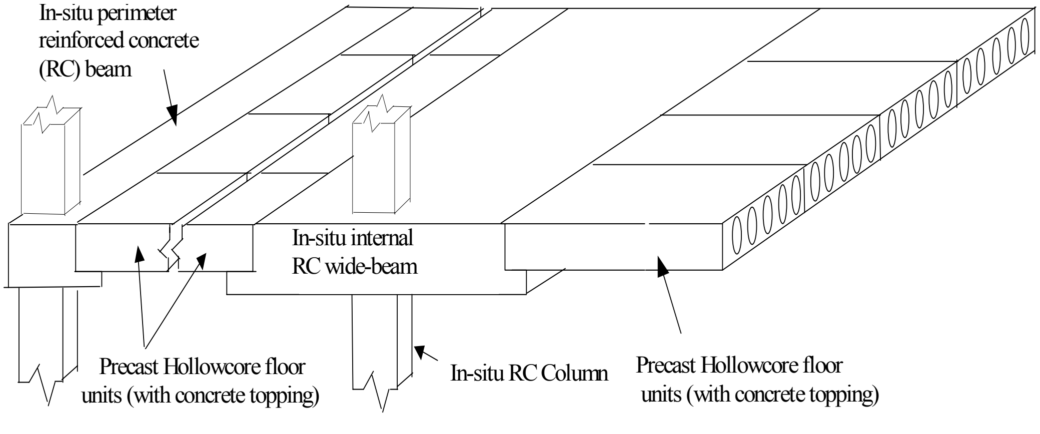

Fig. 1 The precast hollowcore floor system: General Arrangement

2. Importance of time evaluation

Time evaluation of floor design is important because the evaluation would allow different alternative floor systems to be compared and enable the fastest to be selected. If the selected floor design can lead to faster construction and therefore earlier completion of the project, it can bring early revenue to the client (e.g. rental income on floor space) and reduce interest charges on loans. To the contractor (particularly 'design-and-built' contractor), timesaving may benefit him by reducing overheads and other time-related charges. However, timesaving will benefit him/her even more if there is a monetary incentive in the contract for early completion. Conversely, if there is 'Liquidated and Ascertained Damages' (LAD) to pay as stated in the contract, a delay in finishing the job would certainly incur additional costs to the contractor. Besides, time evaluation of a selected floor system would not only allow construction time of the whole floor to be estimated but also provide a good basis for predicting overall construction time for the whole building. This would therefore facilitate early planning of the project right from the conceptual design stage.

Thus, it can be seen that floor selection made during the early design stage can have vital implications on both the duration and cost of the building construction. Therefore it is important that the decision is based on an objective, systematic and sound procedure in which floor construction times are *quantitatively* evaluated, rather than relying on judgment and past experience as no two building projects are the same in any respect.

3. Time estimating model

Estimating or predicting construction times is not easy [10, 9]. Predicting construction time of structural elements at an early stage of the design process is even more so. This is because any method developed for this purpose can only make use of a very limited amount of input information regarding design, quantities, resources and management structure (as this has not been finalized), but yet must be capable of predicting construction time with adequate accuracy. The general approach taken in this research is to emulate models and techniques used by construction planners during the construction planning (post-tender / pre-construction) stage and apply these to suit the early design stage, making some adjustments and assumptions wherever necessary. Among them, the process-based methodology is the most widely used by planners and therefore adopted. Using this model, floor construction time is systematically evaluated by conducting the following tasks [10]:

(1) Identification of construction activities, their sequence and interdependencies
(2) Measurement of the quantity (or volume) of work for each activity
(3) Determination of a construction (or productivity) rate to suit the schedule, and
(4) Selection of appropriate level of resources

Techniques that fall under this category include Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), Precedence Diagramming Method (PDM) (all of which are network techniques) and the Bar (or Gantt) Chart Method. CPM and PERT identify critical paths and estimate times based on a single precedence relationship (i.e. Finish-Start) and do not, in their basic form, take into account overlaps (leads and lags) between dependent activities as commonly found in practice. On the other hand, both the Bar Chart and PDM readily take into account of overlaps between activities by having three different precedence relationships in their procedure (i.e. Finish-Start, Start-Start and Finish-Finish) and should therefore produce more realistic time estimates. Between the two, however, the Bar Chart Method has been chosen as the basis of the evaluation procedure due to its simplicity of use, popularity and familiarity among design engineers.

4. The time evaluation procedure

Essentially, the time evaluation procedure involves the quantification of the following two constituents of floor construction time:

- duration of each activity, which relates to tasks 2,3 and 4 in the process-based model.
- 'lead-in time' between activities, which relates to task 1 in the model

Since the aim in construction is to reduce time, engineers and contractors would strive to reduce activity durations and lead-in times as much as possible, and this is the first assumption made in the procedure.

4.1 Time evaluation bar chart

The procedure is generally illustrated by the bar chart shown in Fig. 2. In the Figure, floor construction consists of five consecutive activities namely Activities 1,2,3,4 and 5. It is assumed that each activity is linked to, or dependent upon, any of its precedent activities. The duration of each of these activities is respectively represented by d_1, d_2, d_3, d_4 and d_5. Activity 2 is said to be a 'precedent' (or predecessor) activity for Activity 3 while Activity 3 is the 'following' (or successor) activity for Activity 2. Activity 3 is linked or ‘tied up’ to Activity 2 (which in turn is linked to Activity 1) meaning that Activity 3 can start only after a certain (minimum) portion of Activity 2 has been executed.

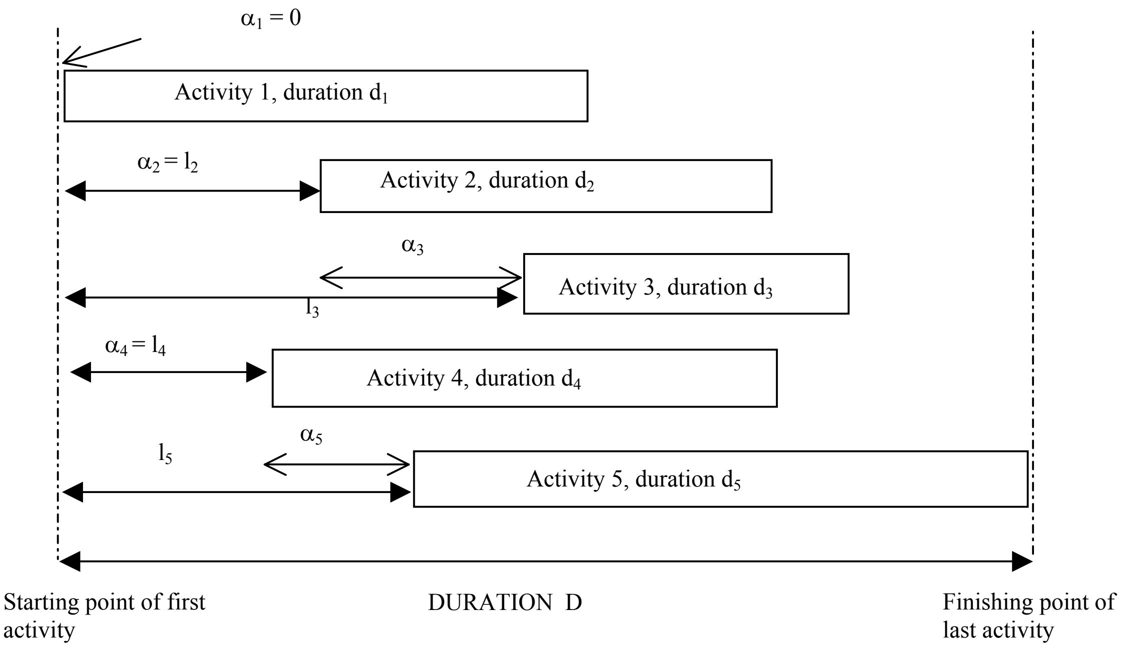

Fig. 2 Time estimating bar chart

For technical, process or other reasons, the delay is necessary and is referred to in this research as the 'lead-in time' for Activity 3, measured relative to the starting point of the linked precedent activity (Activity 2). The lead-in time for Activity 3 is represented by α_3 while l_3 is the *absolute* lead-in time for this activity. The absolute lead-in time is the delay in starting an activity relative to the starting point of *the first activity* in the floor construction and can be obtained by summing the lead-in times (α_i) of successively linked activities, for example, $l_5 = (\alpha_4 + \alpha_5)$ and $l_3 = (\alpha_3 + \alpha_2)$. It is important that only *linked* activities are considered here so that only ‘critical path’ times are measured. Referring to the Figure, the total construction time for the floor system, D, is obtained by adding together the duration of the *last-to-finish* activity (Activity 5 in the Figure) and its absolute lead-in time. Thus,

$D = (d_5 + l_5)$

where

d_5 = duration of the last-to-finish activity (usually measured in days) and

l_5 = absolute lead-in time of the last-to-finish activity (usually measured in days) (= $\alpha_4 + \alpha_5$)

4.2 Procedure for determining duration of each activity

The duration of each activity in the floor construction (length of each bar) is quantitatively evaluated using the commonly used general expression:

$d_i = Q_i / (r_i * p_i)$

where

d_i = duration of activity i, in units of time (i=1,2,3,4…etc)
Q_i = quantity of work associated with activity i, in units of work e.g. m^3 of concreting volume or tonnes of reinforcement installation
r_i = number of resources (e.g. of labour, plant) working on activity i
p_i = planned construction (or productivity) rate measured in units of work per units of time

The work quantity Q_i for each activity is derived using basic data regarding the design of the building (column-to-column grid distance or 'floor span', number of bays in the building, applied loading and estimated cross-sectional dimensions of the floor slab and of any supporting beams). The reciprocal $(1/(r_i \times p_i))$ is given by the average planned construction rate[1] for one gang of workers working on that activity, which may be obtained from experience or suitable published sources e.g. 'price books'. For the purpose of the research, a typical level of r_i has been assumed for each activity and it is also assumed that this level and hence the rate of work, is kept constant throughout the activity.

4.3 Procedure for determining lead-in times

There is little reporting of any method in the literature that can be used to determine lead-in times. Information obtained from practising planning engineers showed that the lead-in times between activities during the construction planning stage is determined by judgment, intuition and past experience, despite the availability of more accurate information regarding design and construction of the project. In order to determine lead-in times in a more objective and rational manner at the early design stage where little is known about the project, a novel technique has been formulated by the author following in-depth discussions with a number of construction experts. The technique relates lead-in times to the floor area formed or 'inscribed' by each activity. The principle is that buildings are built by causing areas to be formed or 'inscribed' through the construction of columns, beams and slab. Knowing the rate at which the areas are formed determines when each activity could start, in terms of the area inscribed by its precedent linked activity, provided that certain requirements are met. For rectangular grid buildings, this floor inscription can be conveniently represented in terms of number of bays, see Fig. 3 below.

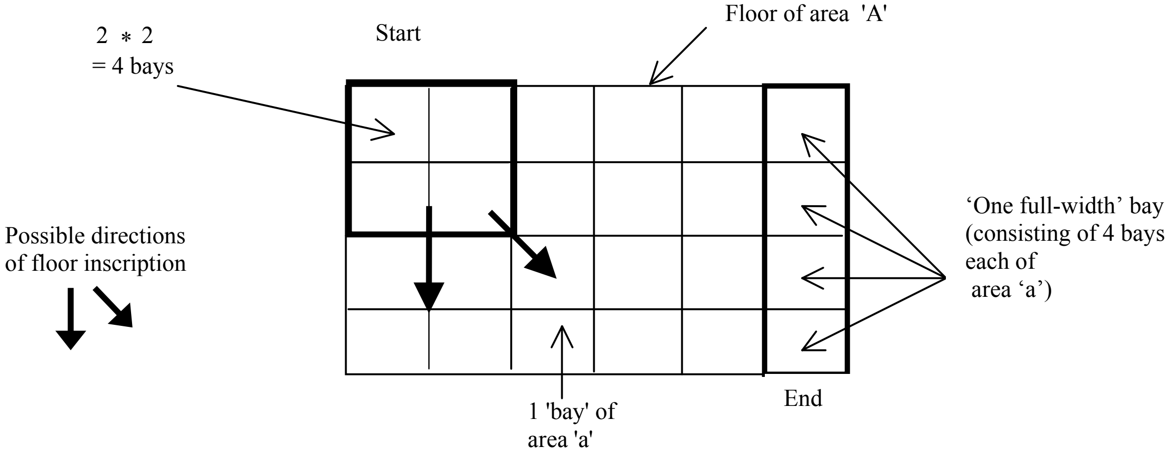

Fig. 3 Representation of floor area by number of bays

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[1] Planned construction rate measures the rate or speed of conducting a particular activity per unit level of resources, as used by planning engineers during the planning (post-tender/pre-construction) stage, and includes both productive and non-productive work. The rate is usually expressed as a ratio of input (e.g. hours of time) to output (e.g. tonnes of reinforcement), for example, 12 hours per tonne of reinforcement.

It is assumed that construction work starts from one corner of the building and thereafter proceeds in either of the two directions shown, as commonly practiced. The number of bays led by the precedent linked activity can then be proportioned to the total number of bays in the floor to obtain the corresponding lead-in time, knowing the duration of the precedent activity. The minimum number of bays led by a precedent activity that would allow a following activity to start is termed in this research the 'lead-in index' 'n' for the following activity.

Thus,

Lead-in index, n = minimum number of bays led by precedent activity, and

Lead-in time $\alpha = \dfrac{n \times \text{duration of precedent activity}}{\text{total number of bays}}$

However, in determining the indices, consideration must be given to any structural, physical or economic requirements that have to be satisfied and the logic of the construction process that needs to be followed. In addressing these, there are three cases of floor inscriptions to be considered, as described in the following section.

4.3.1 Cases of floor inscription: Case1

In this case, the rate of floor inscription by a following activity is *less* than the rate of inscription by the precedent activity as usually found in practice. The result is that the following activity is finished later than its (linked) precedent activity by an amount β_i (termed in this research the 'lag time'), Fig. 4(a). The approach here is to schedule the *start* of following activity as early as possible in order to reduce the delay in finishing this activity, i.e. reduce α_i to reduce β_i. This is a 'start-to-start' precedent relationship, and is called in this research the 'earliest start' approach.

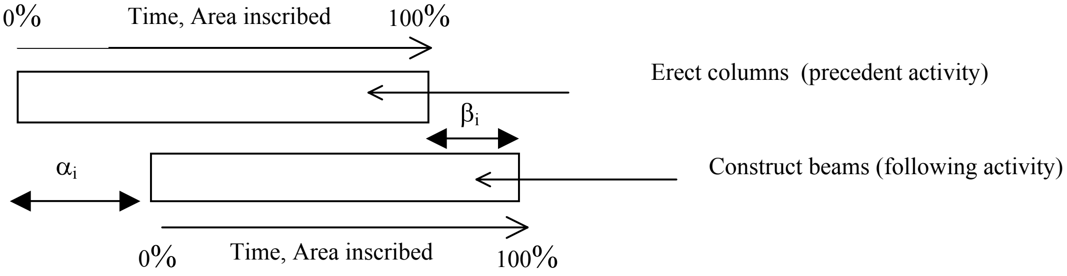

Fig. 4(a) Case 1 floor inscription: Start-start precedent relationship

However, there is a limit as to how early the following activity can commence (the lead-in index), which is usually governed by physical and stability requirements. For example, in Fig.4(a), to start constructing beams, there should be at least two bays of columns already constructed by the precedent activity. This will ensure that the longest straight reinforcing bar (normally 12m) can be placed on the beam formwork. Even if the grid span is longer than 12m, having at least two bays of columns may still be necessary to ensure stability of the beams being constructed.

As an illustration, suppose the lead-in index required for the construction of the beam is 2 ∗ 2 bays = 4 bays (see Fig. 3 for illustration). This means that there must be at least 4 bays of columns already constructed before any beam can be erected in between them. Assuming that there are 24 bays of floor area and that the columns altogether take 6 days to inscribe the whole floor, then

Lead-in time α (for beam construction)

$$= \frac{\text{lead-in index} \times \text{total duration of precedent activity}}{\text{total number of bays}}$$

$$= \frac{4 \times 6}{24}$$

$$= 1 \text{ day}$$

4.3.2 Cases of floor inscription: Case 2

As seen before, the starting point of an activity depends on its lead-in time (α_i) relative to a precedent activity. However, in some cases, the starting point can also be dictated by β_i, for that activity, which measures the delay in *finishing* the activity relative to the finishing point of a linked precedent activity, Fig.4(b) below.

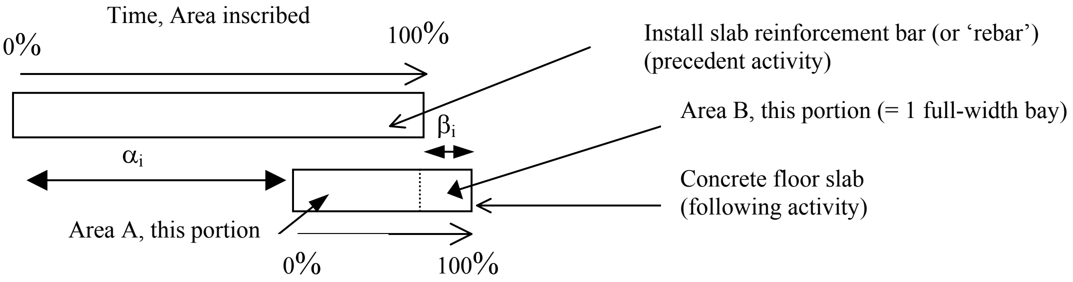

Fig.4 (b) Case 2 floor inscription: Finish-to-finish precedent relationship

This could happen when the rate of floor inscription by a following activity (e.g. 'concrete floor slab' in the Figure) is *greater* than the rate of inscription by its precedent (linked) activity ('installing slab reinforcement' in the Figure). If we schedule the starting point of the following activity using the same approach as in Case 1, the result would be the following activity finishing earlier than its linked precedent activity. This cannot occur in practice as it contravenes the logic of the construction process. The approach taken to determine the lead-in time here is to work backwards, i.e. schedule the *finishing* of the following activity as early as possible and proportion its *area* to determine the lead-in time, i.e. schedule lag time β_i to get lead-time α_i. This 'finish-to-finish' relationship is termed in this research the 'earliest finish' approach. A standard minimum value of one full-width bay area (see Fig. 3 for illustration) has been assigned to the 'lag index' for this case of floor inscription. A lesser area would be too small and uneconomical to construct, or would require more construction joints to be formed.

To illustrate further, if the total duration for the concreting work in Fig. 4 (b) is 3 days, Area B =160m^2, total floor area is = 640m^2 and slab rebar takes 6 days to be installed, then, in terms of areas,

Lag index = 1 full width bay = Area B =160m^2, and
Lag time β_i = [160 / (640)] x 3 = 0.75 day, therefore
Lead-in time α_i = (Duration of slab rebar) - (duration represented by Area A)
= 6 - (3 - β_i)
= 6- (3 -0.75) = 3.75 days

4.3.3 Cases of floor inscription: Case 3

In this case, the following activity is started when *all* of the precedent activity has been completed. This is known as the 'finish-to-start' approach, see example in Fig.4(c) below.

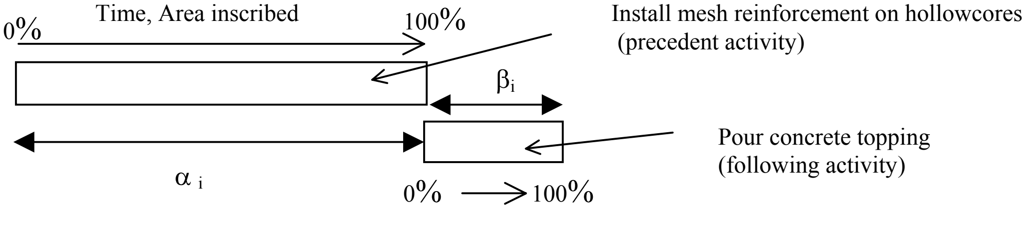

Fig.4 (c) Case 3 floor inscription: Finish-to-start precedent relationship

The lead-in index 'n' by definition is the minimum number of bays led by the precedent activity, which in this case happens to be the total number of bays 'N' in the building floor. Thus,

$$\text{Lead-in time} = \frac{\text{n x duration of precedent activity}}{\text{total number of bays in the floor}} = \text{duration of precedent activity}$$

This case is decided upon by considering process and economic requirements as well as practicality reasons. It does not depend on the rate of the following or precedent activities. For example, in Fig. 4(c), it is more practical to wait until all the mesh reinforcement on the hollowcores has been installed before pouring concrete topping on them. The volume would be too small, and therefore uneconomic, if concrete pouring is carried out in stages.

4.3.4 Proposed lead-in indices

The number and type of construction activities and the inter-dependencies between them differ between floor systems. Therefore different activities will have different lead-in indices, while lead-in indices for the same activity may also differ between different floor systems. Values of lead-in indices have been proposed for different activities under three different categories of floor systems depending on the method and sequence of construction [7]. These are 'isolated beam and slab' construction in which all beams are erected or constructed first before lifting and placing precast floor units on them (e.g. the hollowcore system) ; 'attached beam and slab' construction in which the beams and slab are constructed at the same time; and 'flat slab' construction which does not involve any beam construction. For the purpose of the paper, lead-in indices for 'isolated beam and slab' construction are given in Table 1(a) and Table 1(b) below. Of course the reader may adopt different values from those given if he or she wishes to do so.

Table 1(a) Lead-in indices for' isolated beam and slab' floor system: Activities under column and beam construction

	Activity	Linked precedent activity (see 1st column)	Case(s) of floor inscription	Lead-in index 'n', (in terms of number of bays)	Comments/ Justification on the indices given (based on author's own experience / discussion with planning experts, contractors, etc)
1	Construct columns	-		0	-
	<u>Construct beams:</u>				
2	Erect falsework and soffit formwok	1	1	2 * 2 = 4	To avoid congestion for column construction. Also to accommodate longest bar length (12m) usually needs min. 2 bays.
3	Erect formwork to beam sides	2	1	2 * 2 = 4	To follow activity 2
4	Install beam rebar	3	1	2 * 2 = 4	To accommodate longest bar length (12m) usually needs min. 2 bays
5	Pour concrete	4	2 (typical)	No. of bays in last full- width bay	To ensure a minimum practical area for pouring concrete
			1	2 * 2 = 4	assumes 'split 'concreting
6	Curing and strength gaining	5	3	Total number of bays N	Activity can only start after all concrete has been poured
7	Striking side formwork	6	3	-	9.5 work hours + overnight
8	Lift and connect precast/steel beam	1	2 (typical)	No. of bays in last full- width bay	Stability + practicality
			1	3 * 3 = 9	Stability

Table 1(b) Lead-in indices for' isolated beam and slab' floor system: Activities under slab construction

	Activity (Activity number continued from Table 1(a))	Linked precedent activity (see 1st column)	Case(s) of floor inscription	Lead-in index 'n', (in terms of number of bays)	Comments / Justification on the indices given (based on author's own experience / discussion with planning experts, contractors, etc)
	Construct floor slab				
9	Lift and position floor units	6 or 8	3	Total number of bays N	Few follow-up activities, so can start later after all are lifted
10	Seal joints (grout) and install tie bars	9	3	Total number of bays N/2	Final positioning of units may only be confirmed after half have been installed.
11	Install mesh	10	3	Total number of bays N	Mesh cannot be installed if all joints below have not been sealed. To optimise crane use, wait until all units lifted
12	Pour concrete topping	11	3	Total number of bays N	Small amount normally involved, so all can be done in one operation
13	Curing/strength gaining	12	3	Total number of bays N	Need to pour all concrete before curing
14	Remove beam falsework	13	3	-	Not part of floor cycle time calculations

Validation

During the period of the study, the time evaluation procedure has been tried on several types of floor systems. However for most of the systems, it has been difficult to find on-going building projects to compare with. Despite the above difficulties, some effort has been made to validate the accuracy of the predictions by comparison with two 'real' projects namely the Cardington project[2] (for the in-situ flat slab system) and the MDRB project[3] (for the semi-precast lattice girder planks system). In addition, the accuracy of the predictions for other floors was also validated by using other methods: comparing with available information found in published sources [e.g.11], time estimates given by contractors and for the in-situ flat slab system, outputs given by the software program 'CONCEPT' [12]. Based on the above exercise, it has been found that the accuracy of the predicted speeds fall within 20% of 'real project' figures, which is already considered good for the early stages of design [13,14]. The procedure was also sent to well-known academicians and a number of experts and individuals in the British construction industry (three well-experienced consultant engineers and two established contractors) for general criticism. They all found that the approaches and principles used in the procedure were sound, and would as a whole become a useful and reliable method for evaluating speeds of floor and other similar structural systems, which would subsequently lead to a better choice of these systems.

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[2] This project involved the construction of a seven-storey in-situ reinforced concrete frame building at the Building Research Establishment's Large Building Test Facility in Cardington, Bedfordshire, UK. It served as a research instrument for meeting clients' expectation of 'better value' in construction. The project was started in January 1998 as part of the European Concrete Building research programme.

[3] This is a 9-storey in-situ reinforced concrete frame building situated in Imperial College of Science, Technology and Medicine, London, UK. The frame basically consists of 50mm Lattice girder slabs resting on wide-beams, columns and shear walls. Construction work started in September 1999 and the superstructure was completed in July 2000.

Conclusion

A procedure has been developed that can be used to evaluate or predict construction times of floor or other similar structural systems at the (early) conceptual design stage, and in a more objective and rational manner. It is based on the bar chart technique normally associated with the pre-construction (or post-tender) stage. The procedure is characterised by its innovative and novel technique in quantifying lead-in times between activities by relating them with the ratio of the area led by the precedent activity (i.e. the 'lead-in index') to the total floor area. Some of the time evaluations produced by the procedure have been validated against real-life projects and the procedure has been shown to be able to produce sufficiently accurate results. The procedure would thus enable design engineers and contractors to compare speeds of different floor systems at the early design stage, and would subsequently assist them in selecting the most construction-efficient system for a particular building configuration. Besides, if adopted by planners during the pre-construction stage, it would significantly improve time estimation and planning of their projects, considering the availability of more complete design and construction information at this stage. Finally, with some modifications, the same concept could also be applied to other non-engineering projects, particularly those involving the consumption of space and time.

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