Systems Thinking and Construction Productivity

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ABSTRACT: *This paper describes research undertaken to investigate the possibility of using systems to model productivity in construction. In particular, it concentrates on the use of systems dynamics and project level productivity. The literature identifies 34 factors affecting productivity but based on a survey of professionals, five of these are recognised as important. They form the basis of a systems model whose development is described. The model includes coefficients produced from analysis of subjective and qualitative views obtained from industry. The results are therefore relative and it would be necessary to validate and calibrate the model for quantitative use in practice.*

Keywords: Construction productivity, system dynamics, productivity factors, construction management

INTRODUCTION

Construction is among the world's largest and most challenging industries. In different forms, it holds the key to the prosperity of emerging and industrialised countries. It is also a large user of national resources. Building and civil engineering turnover involving design services, contracting and materials manufacture represent around 10% of GNP of most nations (Olomolaiye et al. 1998) and even in the poorer countries, the net output of construction alone is between 3% and 6% of GNP (Harvey and Ashworth 1997). The provision of an infrastructure is an essential part of development; the maintenance and change of the infrastructure to cater for the changing demands of the rapidly changing world are essential to maintain developed status.

It is not surprising then that construction productivity has formed a major research area for a considerable time (Olomolaiye et al. 1998). However, despite all this research effort, there appears to be a broad consensus that there has been a decline in productivity in the construction industry in several countries in recent decades (see for example Business Roundtable Publications 1991 for comments on the US construction industry). In the UK the government has recognised that there is considerable scope for improvement (Latham 1994).

Improvement in productivity will not be achieved without bearing in mind that there is an enormous number of factors affecting productivity and that there is a necessity to locate the most influential ones among them. Doing so will enable the researchers to pinpoint the areas where efforts are to be directed in order to reach the optimum productivity of the studied project.

This paper describes an attempt to model construction productivity and all the factors which affect it as a system. The sources of data are outlined and a method of using the model to help managers is presented.

CONSTRUCTION PRODUCTIVITY

The definition of construction productivity is difficult. Using the engineering analogy of efficiency, which is defined as:

$$Efficiency = \frac{Output}{Input}$$

appears reasonable until the input is considered when it becomes apparent that one could include many resources such as labour, plant and equipment, materials, management, fuel etc. some of which are very difficult to quantify. Despite the difficulties, this definition is used to gauge the overall productivity of an industry or organisation Productivity defined in this way is called Total productivity. At project level however, it is not very useful and it is more common to consider the productivity of a subgroup of the inputs and outputs. For example, the productivity of labour or the productivity of concrete works. For this purpose, the single-resource productivity measures the productivity of a single resource such as labour (partial productivity is the equivalent when more than one but not all the aspects are included). Thus:

$$Total\ Productivity = \frac{Total\ Output}{Total\ Input} \qquad Single\ Resource\ Productivity = \frac{Total\ Output}{Total\ Input\ by\ the\ Resource}$$

These are discussed more fully by Olomaiye et el (1998). They further suggest that whilst the economic productivity (in which both input and output are considered in terms of money) is easier to calculate, it is the physical productivity (such as that of labour on concrete works) which enables a manager to control the construction process. This paper deals with partial physical productivity although it could be adapted to work with total productivity.

FACTORS AFFECTING CONSTRUCTION PRODUCTIVITY

Low or high productivity in a construction project is not the effect of a single variable, or factor, but a set of variables interacting with each other to produce the final result. Such complexity requires a thorough study of these factors in order to understand both the individual factors and their interaction.

Table 1 shows some of the factors which other authors have recognised as being potentially important and which might be classified as 'managerial'.

Productivity Factors	References
M.1 Planning	Olomolaiye et al., 1998; Noyce 1997, ECI 1994
M.2 Control	Olomolaiye et al., 1998; Rau, 1988; Lucas and Barstad 1983
M.3 Good communications	Rau, 1988
M.4 Material management	Dieterle and DeStephanis, 1992, Olomolaiye and Harris 1995
M.5 Material movement	Thomas et al., 1990; Neil, 1986; Muehlhausen, 1991
M.6 Crew interference	Thomas et al., 1990; Harranein 1997

Table 1: Management based productivity factors

Although several authors (for example Olomolaiye 1998) have recognised the importance of several factors no author has considered the relative importance of the factors. This is a fundamental problem in the understanding of construction productivity and the starting point for the work described in this paper.

OBTAINING THE INFORMATION TO MODEL PRODUCTIVITY

In order to produce a systems model, it is necessary to determine the importance of the individual factors, their interrelationships with one another and their effect on productivity itself.

The importance of the factors and their interrelationships were obtained by asking construction professionals including engineers (designers and contractors), managers, quantity surveyors and academics. To be certain that the conclusions drawn were realistic, a considerable amount of information was required from each person and a survey using traditional questionnaires or interviews would be inappropriate (Bryman 1989). In an attempt to overcome the shortcomings of the more traditional methods, a form, part of which is shown in Figure 1, was used.

The form was designed to collect the strength of the influence of the factors in the rows has on the factors in the columns. Based on an initial survey of a limited number of professionals and the review of the literature, thirty-four factors were selected for consideration. Conceptually therefore, there are 34*34 (=1156) pieces of information to be collected from each respondent. In reality however, not all of these are possible. For example, the weather can affect absenteeism, communications and safety but none of the factors considered can affect the weather. There is not, therefore, a one-to-one correspondence between the rows and columns in the form.

In addition, the 'leading diagonal' elements were not allowed to take any value. It is recognised that this could be a limitation because, for example, absenteeism could affect future absenteeism but the effects are not considered to be great in the final model.

The volunteer respondents were selected from a range of backgrounds and were asked to fill in the form indicating the strength (high, medium, low or none) of the relationships that they believed existed between the factors.

The results were analysed using a two step procedure to produce numerical values for the interaction between the factors. The first stage was to convert the qualitative responses to numerical values. A 4-point scale was used with 4 being a high level of interaction and 1 being very little. The second step was the normalisation of the respondents' answers to remove personal biases. Table 2 shows an abstract of the results of the analysis. As in table 1, only a portion of the complete table is provided here. The larger the number in any cell, the greater the interaction between the factors represented by the row and column of the cell. Thus 'planning' has a large effect on 'control' (value 5.6) and 'control' has a smaller but still large effect on 'planning' (value 4.75).

- Fill in the matrix to show the interactions of the factors. For example if you think the 'weather' has a large effect on 'absenteeism' enter H (for high) in the cell in the weather column and absenteeism row. - Show the effects as H for high, M for medium and L for low. For no effects leave the cell blank.	ABSENTEEISM	DISRUPTIONS	LEVEL OF SKILLED LABOUR	USE OF EQUIPMENT	OVER TIME	LENGTH OF WORK DAY	NUMBER OF FOREMAN ON SITE	CREW SIZE	MOTIVATION	LEARNING CURVES	COMMUNICATIONS	DESIGN & BUILDABILITY	INTERFERENCE BY OWNER	RESTRICTED ACCESS	CHANGE ORDERS	ACCELERATION OF PERFORMANCE	DIFFERING SITE CONDITIONS	SAFETY	WORK INSPECTION BY ENGINEER	MATERIAL MANAGEMENT	CONTROL OF THE PROJECT	PLANNING
ABSENTEEISM			M				L		M				L		L	L		L			L	L
DISRUPTIONS			L				L		L		M	M	M	L	M	L	M	L		L	L	M
LEVEL OF SKILLED LABOUR							L		L						L	L					L	
USE OF EQUIPMENT							L															
OVER TIME																						
LENGTH OF WORK DAY																						
NUMBER OF FOREMAN ON SITE			L						L						L	L					L	L
CREW SIZE			L	L					L					L								L
MOTIVATION		M	L	L			L				L	L	L		M	L				L	M	M
LEARNING CURVES		M	L						L			L	L		M	L	L	L			L	L
COMMUNICATIONS		L					L		L			L			L	L						
DESIGN & BUILDABILITY		L	L	L																		
INTERFERENCE BY OWNER												L				L					L	L
RESTRICTED ACCESS																						
CHANGE ORDERS									L			L	L	L		M	L	L		L	L	M
ACCELERATION OF PERFORMANCE	L	L					L	L	L	L	L	L	L	L	L		L	L	L	L	L	M
DIFFERING SITE CONDITIONS																						
SAFETY	L		L				L	L	L	L		L	L	L		L	L		L		L	L
WORK INSPECTION BY ENGINEER		L	M				L				L		L		L	L					L	L
MATERIAL MANAGEMENT																						
CONTROL OF THE PROJECT	M	L					M	M	L	L	L				M	M		M	M			H
PLANNING	M	H					M	L	L	L		M		L	M	L	L	L		L	H	
MODERN MANAGEMENT SYSTEMS																						
CREW INTERFERENCE																						

Figure 1: Extract from form used to elicit relationship information

	Control	Planning	Change Orders	Project size	Commun-ication	Training	Disrup-tions	Technol-ogy	Build-ability	Motiv-ation	Safety
Control	0	5.60	4.72	4.90	4.56	4.23	3.70	0	3.75	0	4.29
Planning	4.75	0	4.43	4.98	4.19	4.08	3.93	0	3.73	0	3.41
Disruptions	4.1	4.91	5.06	0	4.48	0	0	0	0	0	0
Motivation	3.57	3.86	4.08	3.62	3.62	3.78	4.6	0	0	0	3.36
Safety	3.32	4.41	0	3.7	0	4.37	0	4.15	0	0	0
Acceleration	0	3.77	0	0	0	0	3.47	0	3.45	0	0
Learning	0	0	0	0	0	3.43	0	3.91	0	3.7	0
Buildability	0	0	0	0	0	0	0	4.4	0	0	0
Work inspections	0	0	0	0	0	0	0	0	0	0	3.31
Communications	0	3.58	0	3.73	0	0	3.49	0	0	3.56	0
Change orders	3.88	3.37	0	0	0	0	0	0	4.67	0	0

Table 2: Results of analysis of the collected data

	Significant Factors	**Effects on Productivity**
1	Control (P_1)	+6.12
2	Planning (P_2)	+7.24
3	Motivation (P_4)	+5.41
4	Safety (P_5)	+3
5	Disruptions (P_3)	-5.53
Absolute total effect		27.3

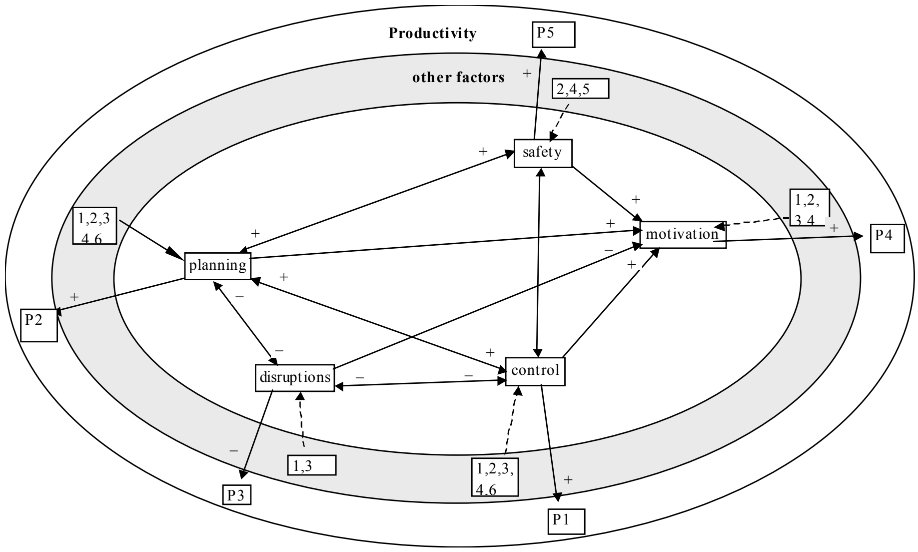
Table 3: Selection of factors and their effects on productivity

Respondents were also asked to suggest the effects on productivity of each of the factors. Once again, this is difficult because of the interaction of the parameters and the variability of their effects from time to time and from project to project. Despite this, the figures provided were considered to be the best available and suitable for use in modelling. In this survey, a scale of 1 to 10 was used with 10 being a large effect and 1 being a small one

The responses were normalised to remove personal bias and the average scores for the factors used to select the most significant factors. These are shown in table 3. The sign indicates whether an increase in the value of the factor increases productivity (+ve) or decreases it (-ve).

THE MODEL

The collection and analysis of the information provided the basis for the system modelling. An outline system diagram for the developed system is shown in Figure 2. In this form it is useful as an indicator of interactions but in order to be of real use it is necessary to model the interactions. This requires numerical values being assigned to the factors and their interaction.



Other Factors: 1 – Change orders; 2 – Size of project; 3 – Communications; 4 – Training; 5 – Construction technology; 6 – Design.

Figure 2: Outline system diagram for selected factors

The variables used in analysis of this model are the five significant factors and the value of productivity. They are not naturally quantified on a construction project and it was therefore necessary to define ranges for the variables. Each was allowed to be in the range 0-10 with 0 being low. Such a scale might appear to be limiting since it is impossible to 'measure' however, managers liked the ability to assess the variables numerically and were satisfied with the accuracy provided. It was an improvement on the situation in which they previously operated.

As stated above, each factor that affects productivity is itself affected by a number of factors. For example, in the model described here, control at any time is a function control in the previous period and planning, safety, motivation, disruptions and other, 'non-significant' variables from the current period. Thus:

$$\text{Control}_R(t) = e_c \times \text{Control}(t-1) + (1-e_c) \times \text{Control}(t) \quad \mathbf{1}$$

Where

Control_R = the resultant Control at period (t)

e_c = a percentage of Control from the preceding period, and

Control (t) = the Control value at period t as a result of other factors from the previous period. Thus:

$$\text{Control}(t) = b_c \times [a_{1,2} \times \text{Planning}(t-1) + a_{1,3} \times \text{Motivation}(t-1) + a_{1,4} \times \text{Safety}(t-1) - a_{1,5} \times \text{Disruptions}(t-1)] + (1-b_c) \times \text{other factors}(t-1) \quad \mathbf{2}$$

Where: b_1 is a coefficient which relates 'significant factors' with the 'other factors'.

$a_{1,2}$, $a_{1,4}$ and $a_{1,5}$ = coefficients which relate significant factor 1, control, with the other significant factors.

Combining equations **1** and **2** gives:

$$\text{Control}_R(t) = e_c \times \text{Control}(t-1) + (1-e_c) \times [b_c \times [a_{1,2} \times \text{Planning}(t-1) + a_{1,3} \times \text{Motivation}(t-1) + a_{1,4} \times \text{Safety}(t-1) - a_{1,5} \times \text{Disruptions}(t-1)] + (1-b_c) \times \text{other factors}(t-1)] \quad \mathbf{3}$$

Similarly:

$\text{Planning}_R(t) = e_p \times \text{Planning}(t\text{-}1) + (1\text{-} e_p) \times [\, b_p \times [a_{2,1} \times \text{Control}(t\text{-}1) + a_{2,3} \times \text{Motivation}(t\text{-}1)$
$+ a_{2,4} \times \text{Safety}(t\text{-}1) - a_{2,5} \times \text{Disruptions}(t\text{-}1)] + (1\text{-}b_p) \times \text{other factors}(t\text{-}1)]$ **4**

$\text{Motivation}_R(t) = e_m \times \text{Motivation}(t\text{-}1) + (1\text{-} e_m) \times [\, b_m \times [a_{3,1} \times \text{Control}(t\text{-}1) + a_{3,2} \times \text{Planning}(t\text{-}1)$
$+ a_{3,4} \times \text{Safety}(t\text{-}1)] - a_{3,5} \times \text{Disruptions}(t\text{-}1)] + (1\text{-}b_m) \times \text{other factors}(t\text{-}1)$ **5**

$\text{Safety}_R(t) = e_s \times \text{Safety}(t\text{-}1) + (1\text{-} e_s)\, [\, b_s \times [a_{4,1} \times \text{Control}(t\text{-}1) + a_{4,2} * \text{Planning}(t\text{-}1) + a_{4,3} * \text{Motivation}(t\text{-}1)$
$+ a_{4,5} * \text{Disruptions}(t\text{-}1)] + (1\text{-}b_s) * \text{other factors}(t\text{-}1)]$ **6**

$\text{Disruptions}(t) = e_d \times \text{Disruption}(t\text{-}1) + (1\text{-} e_d) \times [b_d \times [a_{5,1} \times \text{Control}(t\text{-}1) + a_{5,2} \times \text{Planning}(t\text{-}1)$
$+ a_{5,3} \times \text{Motivation}(t\text{-}1) + a_{5,4} \times \text{Safety}(t\text{-}1)] + (1\text{-}b_d) \times \text{other factors}(t\text{-}1)$ **7**

Productivity in the model is partial productivity defined earlier and using the ideas above provide the following

$$\text{Productivity}_R(t) = c \times \text{Productivity}(t\text{-}1) + (1\text{-}c) \times \text{Productivity}(t) \quad \textbf{8}$$

Where: $\text{Productivity}_R(t)$ = resultant productivity at period (t)

Productivity (t) = productivity at period 't' calculated from the effects of factors in that period

c = percentage found by experimentation

$\text{Productivity}(t) = p_c \times \text{Control}(t) + p_p \times \text{Planning}(t) - p_d \times \text{Disruptions}(t) + p_m \times \text{Motivation}(t) + p_s \times \text{Safety}(t)$ **9**

Where p_c, p_p, p_d, p_m and p_s are coefficients which relate significant factors with productivity.
Substitution gives

$$\text{Productivity}_R(t) = c \times \text{Productivity}(t\text{-}1) + (1\text{-}c) \times [p_1 \times \text{Control}(t) + p_2 \times \text{Planning}(t) - p_3 \times \text{Disruptions}(t) + p_4 \times \text{Motivation}(t) + p_5 \times \text{Safety}(t)] \quad \textbf{10}$$

There is no consideration in the productivity equation for other factors other than the significant ones. These factors have only an indirect effect which is assumed to manifest itself throughout the five significant factors.

		1 Control	2 Planning	3 Motivation	4 Safety	5 Disruptions	'b' coefficients	'p' coefficients
1	CONTROL	0	$a_{1,2} = 0.21$	$a_{1,3} = 0$	$a_{1,4} = 0.16$	$a_{1,5} = 0.14$	b_c=0.38	0.22
2	PLANNING	$a_{2,1} = 0.17$	0	$a_{2,3} = 0$	$a_{2,4} = 0.12$	$a_{2,5} = 0.14$	b_p=0.36	0.27
3	MOTIVATION	$a_{3,1} = 0.13$	$a_{3,2} = 0.14$	0	$a_{3,4} = 0.12$	$a_{3,5} = 0.17$	b_m=0.50	0.11
4	SAFETY	$a_{4,1} = 0.12$	$a_{4,2} = 0.16$	$a_{4,3} = 0$	0	$a_{4,5} = 0$	b_s=0.39	0.20
5	DISRUPTIONS	$a_{5,1} = 0.15$	$a_{5,2}$ 0.18	$a_{5,3} = 0$	$a_{5,4} = 0$	0	b_d=0.48	0.20

Table 4: The equation coefficients

As can be seen the transition equations require three sets of coefficients: 'a', '*b*' and '*p*'. These were all calculated from the information in tables 3 and 4 and are as shown in Table 4.

It is necessary to determine that the behaviour of the model in known situations before it can be used in a predictive mode. However, it is impossible to check that the model is 'correct' and it was decided to check that it gave 'sensible' results in controlled experiments. This was done by producing a spreadsheet model and evaluating control situations which could then be presented to and discussed with practicing engineers.

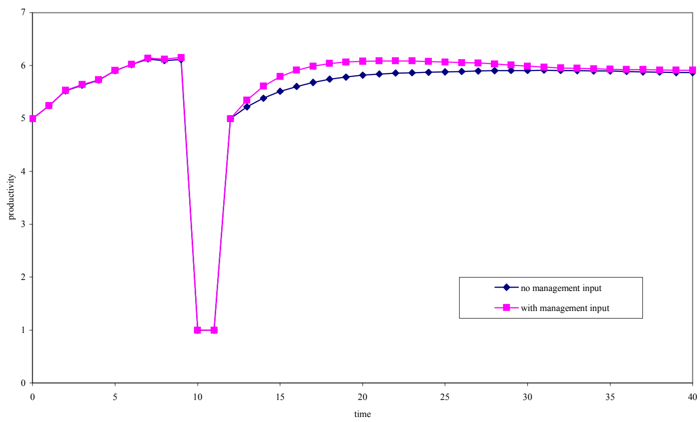


Figure 3: An example of the effect of management strategy

USING THE MODEL TO EVALUATE MANAGEMENT STRATEGIES

Four of the significant factors used to build the model constitute a group which can be described as 'management factors'. Control, planning, motivation and safety are all factors which management of the construction project can manipulate in order to influence the running of projects.

Such manipulation requires greater or less expenditure on each of the factors at the start of the project or sometime throughout the project. How much to spend on each and when to spend it is a management strategy. The systems model can be used to help to evaluate any management strategy in any given project situation.

As an example, Figure 3 shows the predicted effects of a severe disruption on the productivity of a project when both no management action is taken and when management action (here an increase in expenditure on planning) is taken to mitigate the effects. It can be seen that, after the disruption, the 'no management' strategy is slower to return to maximum productivity, and, in both cases, the maximum productivity after the disruption is lower than it was before. Such a result agreed well with the 'feelings' expressed by managers but to obtain numerical values to this managers would have use their own b and c parameters in the equations above and determine their own cost for varying the variables.

CONCLUSIONS

The research has demonstrated that it is possible to produce a systems dynamics model for construction productivity. Initial experiments indicate that the model behaves sensibly but that more experimentation is required to be able to predict absolute rather than relative productivities.

Further work is planned in using the model to assist managers to choose a strategy and to provide a mechanism for evaluating the effects of disruptions.

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