The Effects of Buildability Factors on Rebar Fixing Labour Productivity of Beamless Slabs

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Abstract

Buildability is an important factor affecting labour productivity. Nevertheless, a thorough search of the literature revealed a dearth of research into its effects on in situ reinforced concrete construction, especially at the activity levels. Since rebar fixing is an integral trade of this type of construction material, and beamless slabs are amongst the major encountered activities on construction sites, the objective of this research is to explore the buildability factors affecting its rebar fixing efficiency. To achieve this objective, a large volume of fixing productivity data was collected and analysed using the categorical interaction - regression method. As a result, the main and interaction effects of rebar diameter; reinforcement quantity; slab geometry; and reinforcement layer location are determined. The findings show a significant influence of these factors on the fixing operation, which can be used to provide designers and construction managers with feedback on how well the design of this activity considers the requirements of buildability, and the tangible consequences of designers' decisions on labour productivity.

Keywords: Beamless slabs, Buildability, Categorical interaction-regression, Labour productivity, Rationalisation, Rebar fixing, Standardisation

Introduction

Construction is the world's largest and most challenging industry (Tucker 1986). In 1997, the US construction industry accounted for 10% of the Gross Domestic Product (GDP) and employed over 10 Million, making the industry the largest in the country (Allmon et al. 2000). Since construction is a labour intensive industry, the significance of this influence, clearly justifies the concern over its labour productivity.

Several factors affect labour productivity, but buildability is amongst the most important (Adams 1989; Horner et al. 1989). Buildability, as defined by the Construction Industry Research and Information Association, is "*the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building*" (CIRIA 1983).

Buildable design leads to higher labour productivity and lower construction cost (Carter 1999; Dong 1996; Williamson 1999). Design simplification is achieved through the implementation of the following buildability principles: (a) rationalisation; (b) standardisation; and (c) repetition (Jarkas 2005; Fischer and Tatum 1997; Dong 1996). Design rationalisation is defined as "*the minimisation of the number of materials, sizes, components or sub-assemblies*", whereas standardisation is "*a design philosophy requiring the designed product to be produced from those materials, components and sub-assemblies remaining after design rationalisation* has taken place" (Moore 1996a). The design repetition principle involves repeating bay layout, floor grids, dimensions of elements, and storey height.

Numerous previous studies investigated the influence of buildability on the construction process (Lam and Wong 2009; Saghatforoush et al. 2009; Lam et al. 2007; Trigunarsyah 2007, 2004; Pulaski and Horman 2005; Nima et al. 2002; Cheetham and Lewis 2001; Jergeas and Put 2001; Poh and Chen 1998; Fischer and Tatum 1997; Alshawi and Underwood 1996; Hyde 1996; Moore 1996a, 1996b; CIDB 1995; O'Connor and Victoria 1988; Griffith 1987; O'Connor et al. 1987; O'Connor et al. 1986). Nonetheless, to date, little research has been conducted to investigate and quantify the effects and relative influence of buildability factors on rebar fixing labour productivity of situ reinforced concrete construction, especially at the activity levels. Moreover, most of the previous buildability studies were heuristic in principles, generic and qualitative in nature; a few were even rudimentary, based upon anecdotal perceptions and adopted practice, insights and common sense.

One of the barriers, and perhaps the most important, to the implementation of the buildability concept, is the difficulty in measuring its benefits to the construction industry; the industry still lacks methodologies to represent the requirements for buildability analysis and measurement (Song and Chua 2006).

Although seminal work has been developed, apart from the "Buildable Design Appraisal System (BDAS)", which was established by the Construction Industry Development Board of Singapore (CIDB 1995), previous research has not provided "specific" guidance on how to measure the buildability of a design. In one of the few text books entirely devoted to buildability, Ferguson (1989) shows the breadth of factors which must be considered to make a design buildable and provides many examples of buildability problems and suggestions for improvements. While such suggestions allow the classification of buildability issues according to their level of details, they do not link buildability issues to "specific" design decisions.

Notwithstanding that the BDAS is the only available quantitative design appraisal tool to date, the scientific reliability of the methodology employed in developing the system's buildable scores is questioned. Buildable scores were obtained from inputs provided by government agencies, private consultants, and product manufacturers based upon previous personal and group experience and judgment (Dong 1996). While such an approach can be regarded as good practice and common sense, the scientific method requires facts to be established and supported by rigorous research, measurement and analysis.

Another major shortcoming of this appraisal system stems from the lack of depth in which buildability is assessed. Buildable scores are awarded based on the overall structural type and construction method. Such an approach is too general in nature where the impacts of buildability factors require investigations in far greater depth to establish and quantify their effects on labour productivity. Furthermore, Poh and Chen (1998), in an empirical study of 37 completed buildings, determined inconsistent patterns amongst buildable scores, labour productivity, and construction cost, thus went on to conclude that "*while a design with a high buildable score will result in more efficient labour usage, the relationship between the buildable score and construction cost is less distinct*".

The basic dilemma, the researcher argues, may be attributed to the methodology employed by most related previous research, where the effect of buildability was investigated on a generic basis, which has overlooked the important aspect of the current problem. A practical solution to the problem, the researcher suggests, especially in reinforced concrete projects, where the construction process of such structures are composed of various trades and activities, may be achieved through: (1) investigating and determining the effects and relative influence of buildability factors at the activity or component levels, i.e. foundations, grade beams, columns, walls, beams and slabs, which support and make up the building frame, and are common to each activity, so that the impacts of buildability on such trades and activities can be readily available to designers to provide specific guidance to a particular design decision on the one hand, and the collective effects upon the overall phenomenon of buildability on a global basis may be well supported, established and understood, hence can be implemented with sufficient ease, on the other; and (2) quantifying such effects in measurable terms so that the tangible benefits of buildability principles may be realized and formalized.

Since rebar fixing is an integral, labour intensive, trade of this type of construction, the objective of this study is to investigate the effects and relative influence of the following buildability factors on fixing labour productivity of a frequently encountered activity on construction sites; namely, beamless slabs: (a) rebar diameter; (b) quantity of reinforcement fixed; (c) geometry of slab; and (d) reinforcement layer location, i.e. top and bottom, so that labour cost and benefits related to the application of buildability principles to this activity can be estimated for the various levels both, reliably and with reasonable accuracy.

This paper briefly overviews the rebar fixing operation, introduces the characteristic diameter concept, presents the research method and analysis, provides a discussion of the results obtained, furnishes a set of recommendations geared towards enhancing the design buildability level and improving the rebar fixing labour productivity of this activity, and concludes with recommendations for further research into the influence of buildability on other elements and trades of in situ reinforced concrete structures.

Rebar Fixing Operation Overview

The universal “in situ” rebar fixing mechanism involves placing and tying bars in positions. The most common method of tying the reinforcement is to use soft iron binding wires at selected intersections of bars in footings, walls and slabs, and at intersections of main bars and stirrups or links in beams and columns.

Reinforcing steel fixing is a labour intensive operation which requires a high degree of strength and skill. Firm fixing and holding reinforcing bars in position is essential during concreting. Spacers are used to maintain an adequate concrete cover to protect the reinforcement from rusting and expanding due to air and moisture penetration. The most commonly used type is the plastic spacers which are made to fit particular bar sizes. Mortar blocks may be also used as spacers to ensure the provision of adequate cover. For deep slabs, on site fabricated steel chairs are usually used to support and provide the minimum required cover for the top reinforcement layer.

Depending on the scale of the project and reinforcement level of details, reinforcing steel bars are delivered to construction sites either as straight bars in standard bundles of twelve meters in length and two tons in weight, or cut and bent to sizes and shapes off site. Cutting and bending, and fixing of reinforcement are two distinct activities which may be performed by two different gangs on site. On the other hand, prefabricated reinforcements can be also preassembled into cages which may be lifted and fixed in positions.

Based on the preceding discussion, it can be concluded that the task level difficulty associated with rebar fixing operation largely depends upon whether reinforcement is assembled, placed and tied on sites, or pre-fabricated off sites, where the fixing operation is limited to lifting, centring and securing in required positions. Hence, this investigation focuses on the “in situ” fixing operation where the reinforcement is placed, tied, centred and securely fixed in positions on sites.

Beamless slabs reinforcement commonly consists of a double layer grid of reinforcing bars, i.e. bottom and top, placed at ninety degree and tied at selected intersections in each layer. The Bottom Layer reinforcement grid is fixed first, followed by the required electro-mechanical services. Upon the inspection of the bottom layer reinforcement and other services, top layer supporting chairs are evenly distributed and securely fixed in positions. At this stage, the top layer reinforcement grid is fixed. A typical cross-section of slabs observed is shown in Figure 1.

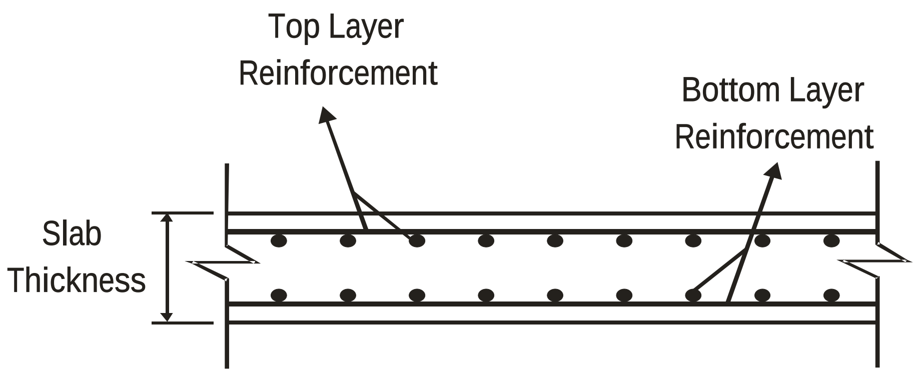

Figure 1Typical Arrangement of Slab Reinforcement

The Characteristic Rebar Diameter Concept

In its most basic form, the “characteristic item” is the largest quantity of an item contained in a work package composed of several items. Horner and Zakieh (1996), found an almost perfect linear relationship between percentage cumulative quantity and percentage cumulative value in two different categories of projects; reinforced concrete bridges, and steel framed supermarkets. The linearity of the relationship indicated that a similar relationship exists between quantity and value, and that any marginal increase in quantity would cause a similar marginal increase in value, especially for large quantity items. It was concluded that the influence of large quantity items would overshadow the effect of any differences in rates of small quantities, and that the relationship is dominated by the rate of the largest quantity. Consequently, the unit rate associated with the largest quantity can be applied to all items within the work package. This item, having the largest quantity within any work package, is referred to as the characteristic item.

The concept of the characteristic item is extremely useful in productivity research and studies. An activity such as rebar fixing is associated with difficulties in productivity measurement due to the variety of bar diameters. Therefore, the application of the “characteristic productivity concept” would greatly simplify the measurement procedure (Jarkas 2005; Lal 1999). The application of the characteristic productivity concept to reinforcing steel trade involves identifying the rebar diameter which accounts for the majority of the quantity, i.e. tonnage, thus referring to as the “characteristic diameter”, and basing the productivity measurement on the assumption that the productivity of all other bar diameters is represented by the productivity of the characteristic diameter. This approach yields negligible error as the large quantity of the characteristic diameter would swamp the small quantities of all other diameters (Horner and Duff 2001), hence was applied throughout this research project.

Research Method and Analysis

The labour productivity data were collected at both levels; macro, and micro. Macro-level observation involves monitoring the overall activity within the trade, where the total productive labour inputs associated with completing the overall activity is recorded, therefore, a single labour productivity index is achieved, i.e. quantity of reinforcement fixed (kg) per man-hour (mh). Labour inputs collected at this level included both; “contributory time”, i.e. time spent in setting-out, preparing work areas, transporting reinforcing steel bars within the site, reading plans and details, as well as “direct or effective time” used to work out the activity, i.e. fixing reinforcement in positions (Jarkas 2005; Chan and Kumaraswamy 1995; Salim and Bernold 1994). Micro-level observation on the other hand, focused on the direct observation of pre-selected elements within the activity. Therefore, the contributory time had negligible effect at this level of observation where only direct productive labour inputs spent to achieve the outputs are used in quantifying the labour productivity of elements observed.

The advantages of monitoring an activity at the micro-level are twofold: (1) the results obtained would assist in cross-referencing patterns depicted from the macro-level observation analysis, which may further provide a better understanding of the overall phenomena and findings of the explored factors influencing the activity; and (2) the impacts of other, non-buildability factors, e.g. communication complexity, sequencing problems, and proportion of work subcontracted, on labour productivity are minimized at this level of observation.

Since numerous factors, other than buildability, influence labour productivity on sites (Horner et al. 1989), which may mask or even overshadow the effect of buildability on the rebar fixing operation, the focus was on selecting construction projects which shared common features such as, contract procurement method, geographical locations, and to a large extent, construction methods, yet differed in types and magnitudes, so that the impacts of the explored buildability factors could be unravelled; similar sites, largely share similar characteristics of buildability factors, especially at the activity levels, therefore, their effects may not be best revealed.

On the other hand, the differences in management procedures applied amongst the various types and magnitudes of sites observed, have little effect at the activity level of observation, whereas the possible effects of other interfering factors such as, skill of labours, gang size, site layout, and supervision quality, can be moderated by collecting a large volume of labour productivity data (Jarkas 2005). Consequently, sites observed included residential and office buildings, commercial centres, and industrial facilities.

Moreover, to minimize the negative influence of interruptions and disruptions on labour productivity, which can further mask the influence of buildability on the rebar fixing operation, major encountered delays were recorded and discounted from both, macro and micro-level total labour inputs, where only productive inputs were used to quantify the labour productivity indices of the activity.

The buildability factors investigated, which are common to this activity, included: (a) rebar diameter; (b) quantity of reinforced fixed; (c) slab geometry; and (d) rebar layer location. As was previously explained, the rebar diameter effect was presented by the characteristic diameter, whereas the reinforcement quantity was presented by the physical weight of reinforcement fixed.

Since rectangular slab geometry is the most encountered shape on construction sites, the distinction is made between this shape and all other geometries. Although the level of fixing complexities is different amongst other non-rectangular shapes, i.e. trapezoidal, triangular, circular, amongst others, such geometries are least encountered on sites. Therefore, classifying all these shapes into one category, in comparison with the volume of rectangular shapes normally encountered, would yield reasonably accurate conclusion. In view of the aforementioned, this factor was presented by two categorical variables; rectangular, and non-rectangular.

The reinforcement layer location indicates the position of the observed layer, i.e. bottom or top. As with the slab geometry, this qualitative factor was further classified into two categories; bottom, and top.

The productivity data of this activity, which were part of a larger research project, were collected from sixty-seven different construction sites located in the State of Kuwait, where in situ reinforced concrete is the prevailing type of construction. The data collection duration spanned over a period of nineteen months, in which, a total of 130 and 200 labour productivity data points were collected at the macro and micro-levels respectively. Such a large volume of data made it possible to achieve valid, reliable and robust statistical results.

Macro and micro-levels labour inputs for the corresponding slabs observed were collected using the intermittent and direct observation techniques respectively (Jarkas 2005; Williamson 1999; Munshi 1992; Noor 1992). Upon prior arrangements with management personnel of sites selected for observation, specifically designed data collection forms were distributed to rebar fixing gang leaders and members to systematically and consistently record the essential productivity parameters of the labour inputs for the various slabs monitored, and document major delays encountered during the fixing operation.

The intermittent observation technique involved collecting the macro-level labour inputs upon the completion of the activity, yet conducting occasional site visits during the process of the fixing operation to ensure that data collection forms are filled out regularly by gang leaders, and assess the physical progress of activities under observation. The direct observation method on the other hand, focused on collecting the corresponding fixing labour inputs of the reinforcement layer observed, i.e. top and bottom. Micro-level labour inputs, which were filled out by operating gang members, were collected upon the completion of the fixing operation of reinforcement layers observed.

The data collected at the macro-levels were cross-checked by both; site foremen, and charge hands, whereas micro-level data were double-checked by different gang members, who were also involved in the fixing operation of reinforcement layers monitored, for verification and accuracy. Furthermore, slabs observed were visually inspected and marked on drawings for output measurements.

All labour inputs collected were screened for possible measurement errors or outliers, i.e. an unusual observation which lies outside the range of the data values. The outputs of buildability factors explored were determined by the researcher using the “physical unit of measurement” technique (Talhouni 1990). The rebar fixing labour productivity indices of the elements observed were then quantified as shown in equation (1).

$$Labour\ productivity(kg/mh) = \frac{Reinforcement\ quantity\ \ fixed\ (kg)}{Labour\ input\,(\ man\text{ - }hour\ )} \qquad \text{Eq. 1}$$

The screened data were entered into a spreadsheet where the regression analyses were conducted using the "*PHStat*" software, a statistics add-in for Microsoft® Excel. Normal probability plots of labour productivity data revealed that the values belong to almost normally distributed populations, thus validating the statistical reliability inferences. A sample plot of the macro-level rebar fixing labour productivity of slabs observed is shown in Figure 2.

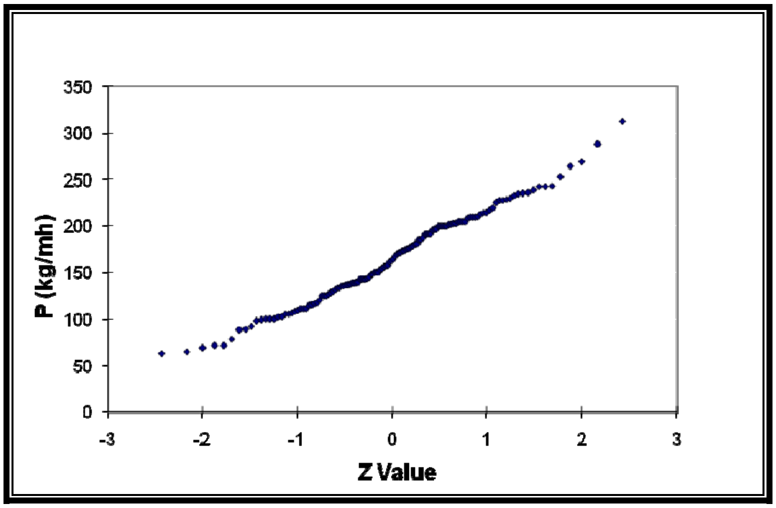

Figure 2 Normal Probability Plot of Macro-level Rebar Fixing Labour Productivity

The main and interaction effects of the investigated buildability factors were analysed using the categorical interaction-regression method (Jaccard and Turrisi 2003; Gujarati 1995; Hardy 1993; Lawrence 1992; Aiken and West 1991; Sanford 1985; Friedrich 1982). Since the slab geometry and reinforcement layer location are categorical, i.e. qualitative, factors, binary dummy variables, which assume the values of either 0 or 1, e.g. 0 if the slab geometry is rectangular and the observed layer of reinforcement is at the bottom level, and 1 if the slab is non-rectangular in shape and the reinforcement is at the top level, were introduced into the regression model to quantify the average difference in labour productivity amongst the categories. The coding however is arbitrary and it would be just as valid to switch the coding criteria, e.g. 1 for rectangular slabs and bottom layer level, and 0 for non-rectangular and top layer level of reinforcement.

Main effects regression models assume no interaction between the independent variables and therefore the unique effect of each independent variable on the dependent variable is quantified while all other independent variables in the model are held constant. However, there are many cases when the effect of an independent variable on the dependent variable depends on the level or intensity of another independent variable in the model (Aiken and West 1991). When such a situation is encountered, an interaction term between the two independent variables is added to the model to incorporate their joint effect on the dependent variable, over and above their separate effects. An interaction term is added in the model as a cross product of the interacting variables. A typical regression model involving interaction between continuous and dummy variables has the basic form shown in equation (2) (Jaccard et al. 1990).

$$Y = b_0 + b_1 X_1 + b_2 D_2 + b_3 (X_1 * D_2) \qquad \text{Eq. 2}$$

Where X_1 is a continuous variable; D_2 is a dummy variable; and $(X_1 * D_2)$ is an interaction term between X_1 and D_2; the interaction coefficient b_3, quantifies the average difference in the slope, i.e. rate of change, of the relationship between the continuous independent variable X_1 and the dependent variable *Y* for the two categories represented by the dummy variable D_2.

Even though we have shown the most commonly encountered interaction case in this model, i.e. interaction between continuous and dummy variables, interaction can occur between two continuous or two dummy variables. Moreover, a multiple regression model may involve several interaction terms.

Due to the observed complexity and additional labour input associated with rebar fixing in non-rectangular slabs, an interaction term between the slab geometry and quantity of reinforcement fixed was assumed and included in the regression model of the corresponding level of analysis, i.e. macro and micro. This term unravels the impact of reinforcement quantity on fixing labour productivity, over and above its separate effect, for the two categories of slab geometry; rectangular, and non-rectangular.

Since the multiple regression models involve several independent variables, i.e. buildability factors, having different units of measurement, a direct comparison of the size of various coefficients to assess the relative influence on the dependent variable, i.e. labour productivity, could be spurious. Therefore, before a meaningful investigation can be conducted, the regression coefficients of the independent variables must to be standardised (Kim and Feree 1981). The standardised regression coefficients are then measured on the same scale, with a mean of zero and a standard deviation of one, and thus are directly comparable to one another with the largest coefficient in absolute value indicating the greatest influence on the dependent variable. A regression coefficient is standardised as shown in equation (3).

$$b_k^* = b_k \left(\frac{s_k}{s_y} \right) \qquad \text{Eq. 3}$$

Where b_k^* is the standardised regression coefficient of the k^{th} independent variable; b_k is the regression coefficient of the k^{th} independent variable; s_k is the standard deviation of the k^{th} independent variable; and s_y is the standard deviation of the dependent variable. Commonly, standardised regression coefficients are referred to as beta weights.

Furthermore, to determine the relative influence of such factors, the most influential factor was chosen as the reference factor, and was assigned the value of 1.00. The relative influence of each factor was then measured relative to the reference factor as shown in equation (4).

$$Relative\ influence\ of\ the\ k^{th}\ factor = \frac{Standardised\ coefficient\ value\ of\ the\ k^{th}\ factor}{Standardised\ coefficient\ value\ of\ the\ reference\ factor} \qquad \text{Eq. 4}$$

The reliability of the regression relationships was determined by conducting statistical significance tests at 5% significance level. The extent to which the data disagree with the null hypothesis, i.e. the regression coefficient of the corresponding buildability factor within the regression model is insignificantly different from zero, thus its effect on labour productivity is statistically insignificant, was determined by the p-value obtained for each factor investigated. The smaller the p-value of the corresponding factor, the greater the extent of disagreement between the data and the null hypothesis, and the more significant the result is. In general, if the p-value of the regression coefficient is less than the significance level, i.e. p-value < 0.050, the null hypothesis is rejected in favour of the alternate hypothesis, that is the impact of the corresponding buildability factor explored upon labour productivity is statistically significant (Sincich et al. 2002).

Furthermore, the goodness of fit of the regression models was assessed by the correlation and determination coefficients. The correlation coefficient, measures the strength of the linear correlation between the dependent and independent variables in the regression model, whereas the coefficient of determination indicates the percent of variance in the dependent variable which can be explained by the independent variables of the model. The higher the coefficients of correlation and determination in the regression model, the better the goodness of fit. The algebraic sign of the regression coefficient on the other hand, denotes the direction of the corresponding buildbability factor's effect on labour productivity, i.e. positive or negative.

Macro-Level Observation Analysis

A total of 130 labour productivity data points were collected at the macro level. The relationship between fixing labour productivity and the buildability factors was determined by the multiple categorical interaction-regression model shown in equation (5).

$$P(kg/mh) = b_0 + b_1\, CBDia + b_2\, TQ + b_3\, Geom + b_4\,(Geom * TQ) \qquad \text{Eq. 5}$$

Where *CBDia (mm)* is the characteristic rebar diameter; *TQ (kg)* represents the total quantity of reinforcement fixed in both layers; *Geom* is a dummy variable, which quantifies the average difference in fixing labour productivity between non-rectangular and rectangular slabs. It assumes the value of 0 if the slab is rectangular, and 1 if non-rectangular; and *(Geom ∗ TQ)* is an interaction term, which quantifies the average difference in the slope of the relationship, i.e. rate of change, between labour productivity and quantity of reinforcement fixed, for the two categories of slab geometry.

The overall regression model and coefficients statistics are presented in Tables 1 and 2 respectively.

Correlation Coefficient (R)	*91.09%*
Coefficient of Determination (R^2)	*82.97%*
Standard Error	*21.48*
F(4,125)	*152.25*
p-value	*0.000*
No. of Observations	*130*

Table 1 Overall Regression Model Statistics for Macro-Level Rebar Fixing Labour Productivity of Beamless Slabs

Coefficient	Value	Standard Error	p-value	VIF[1]	Standardised Coefficient Value	Influence Rank	Relative Influence
CBDia (mm)	7.43	0.556	0.000	1.77	0.656	1	1.00
TQ (kg)	0.000492	0.000	0.000	1.52	0.241	2	0.37
Geom	-20.78	5.56	0.000	1.99	N/A[2]	N/A	N/A
(Geom∗ TQ)	0.000761	0.000	0.00201	2.06	N/A	N/A	N/A

Table 2 Regression Coefficients Statistics for Macro-Level Rebar Fixing Labour Productivity of Beamless Slabs

Notes: [1]Variance inflation factor indicates the correlation amongst the independent variables in the model.
[2]Dummy variables are used to quantify differences in levels between or amongst categories, therefore, the normal interpretation for standardized coefficients does not apply.

The relationship between rebar fixing labour productivity and the relevant buildability factors was therefore quantified by the regression model shown in equation (6).

$$P(kg/mh) = 51.72 + 7.43\,CBDia + 0.000492\,TQ - 20.78\,Geom + 0.000761(Geom * TQ) \quad \text{Eq. 6}$$

In order to quantify the average percentage difference in fixing labour productivity between non-rectangular and rectangular slabs, the average values of the corresponding buildability factors shown in Table 3, were substituted into equation (6) as follows:

Geometry of Slab	Average Characteristic Bar Diameter (mm)	Average Total Quantity of Reinforcement Fixed (kg)
Rectangular	15.29	18192.33
Non-rectangular	13.39	14164.13
Total	14.62	16766.97

Table 3 Average Values of Buildability Factors Influencing Macro-Level Rebar Fixing Labour Productivity of Beamless Slabs

Non-rectangular Slabs, Geom = 1:

$$P(kg/mh) = 51.72 + 7.43(13.39) + 0.000492(14164.13) - 20.78(1)$$
$$+ 0.000761(1 * 14164.13) = 148.18$$

Rectangular Slabs, Geom = 0:

$$P(kg/mh) = 51.72 + 7.43(15.29) + 0.000492(18192.33) - 20.78(0)$$
$$+ 0.000761(0 * 18192.33) = 174.28$$

Therefore, the average difference in fixing labour productivity was determined as shown in equation (7).

$$\left[\frac{(174.28 - 148.18)}{174.28}\right] * 100 = 14.98\% \quad \text{Eq. 7}$$

In comparison with rectangular slabs, an average loss in labour productivity of approximately 15% is associated with reinforcement fixing in non-rectangular slabs.

Table 1, shows strong correlation and high determination coefficients between the investigated factors and labour productivity, i.e. 91.09% and 82.97% respectively. Table 2 further shows that all the investigated buildability factors, including the interaction effect, are statistically significant in their effects on labour productivity, i.e. p-value < 0.050. In addition, the influence rank determines a greater effect of rebar diameter on labour productivity than the total quantity of reinforcement fixed.

Micro-Level Observation Analysis

At this level of observation, 200 labour productivity data points were collected and analysed. In addition to cross-referencing the patterns of results obtained from the macro-level analysis and limiting the effects of non-buildability factors on fixing labour productivity, the purpose of this observation was to quantify the average difference in fixing labour productivity between top and bottom layers. Consequently, the productive labour input of fixing the reinforcement in each layer was collected separately, and the fixing labour productivity of each layer was determined based on the quantity of reinforcement fixed in the observed layer and its associated labour input.

In addition to the buildability factors explored at the macro-level, micro-level analysis included the reinforcement layer location factor. Therefore, the relationship between the buildability factors and labour productivity was determined by the multiple categorical interaction-regression model shown in equation (8).

$$P(kg/mh) = b_0 + b_1\,CBDia + b_2\,Q + b_3\,Geom + b_4\,(Geom * Q) + b_5\,LLoc \qquad \text{Eq. 8}$$

Where *CBDia (mm)*, *Q (kg)* and *Geom* are, as previously defined, the characteristic bar diameter, quantity of reinforcement fixed in the observed layer, and the slab geometry respectively. *LLoc* is a categorical dummy variable, which represents the location of the reinforcement layer observed and quantifies the average difference in fixing labour productivity between the top and bottom layers. This factor assumes the value of 0 if the monitored layer is at the bottom level of the slab, and 1 if at the top.

The overall regression model and coefficients statistics are presented in Tables 4 and 5 respectively.

Correlation Coefficient (R)	*89.71%*
Coefficient of Determination (R^2)	*80.49%*
Standard Error	*25.96*
F(5,194)	*160.04*
p-value	*0.000*
No. of Observations	*200*

Table 4 Overall Regression Model Statistics for Micro-Level Rebar Fixing Labour Productivity of Beamless Slabs

Coefficient	Value	Standard Error	p-value	VIF	Standardised Coefficient Value	Influence Rank	Relative Influence
CBDia (mm)	8.71	0.619	0.000	2.06	0.641	1	1.00
Q (kg)	0.000871	0.000173	0.000	1.71	0.209	2	0.33
Geom	-27.26	5.37	0.000	2.05	N/A	N/A	N/A
(Geom∗Q)	0.00157	0.000452	0.000	2.34	N/A	N/A	N/A
LLoc	-37.28	3.73	0.000	1.02	N/A	N/A	N/A

Table 5 Regression Coefficients Statistics for Statistics for Micro-Level Rebar Fixing Labour Productivity of Beamless Slabs

The relationship between fixing labour productivity and the buildability factors were quantified by the regression model shown in equation (9).

$$P(kg/mh) = 57.55 + 8.71\,CBDia + 0.000871\,Q - 27.26\,Geom + 0.00157\,(Geom * Q) - 37.28\,LLoc \quad \text{Eq. 9}$$

The average difference in fixing labour productivity between the top and bottom layers of reinforcement was quantified, for the relevant category of slab geometry, by substituting the average values of the corresponding buildability factors shown in Tables 6-a and 6-b, into equation (9) as follows:

Layer Location	Average Characteristic Bar Diameter (mm)	Average Total Quantity of Reinforcement Fixed (kg)
Bottom	13.95	9380.42
Top	14.82	10942.69
Total	14.35	10090.55

Table 6-a Average Values of Buildability Factors Influencing Micro-Level Rebar Fixing Labour Productivity of Rectangular Beamless Slabs

Layer Location	Average Characteristic Bar Diameter (mm)	Average Total Quantity of Reinforcement Fixed (kg)
Bottom	13.39	7454.35
Top	14.73	9353.03
Total	13.95	8247.47

Table 6-b Average Values of Buildability Factors Influencing Micro-Level Rebar Fixing Labour Productivity of Non-Rectangular Beamless Slabs

Quantifying Difference in Labour Productivity between Top and Bottom Reinforcement Layers in Rectangular Slabs

The average difference in labour productivity between top and bottom layers fixed in rectangular slabs, i.e. Geom = 0, was quantified as follows:

Top Layer, LLoc = 1:

$$P(kg/mh) = 57.55 + 8.71(14.82) + 0.000871(10942.69) - 27.26(0) + 0.00157(0 * 10942.69) - 37.28(1) = 158.88$$

Bottom Layer, LLoc = 0:

$$P(kg/mh) = 57.55 + 8.71(13.95) + 0.000871(9380.42) - 27.26(0) + 0.00157(0 * 9380.42) - 37.28(0) = 187.22$$

Accordingly, the average percentage difference was determined as shown in equation (10).

$$\left[\frac{(187.22 - 158.88)}{187.22}\right] * 100 = 15.14\% \qquad \text{Eq. 10}$$

An average loss of approximately 15% in labour productivity, compared with the bottom layer, is realized in fixing the top layer reinforcement of rectangular slabs.

Quantifying Average Percentage Difference in Labour Productivity between Top and Bottom Reinforcement layers in Non-rectangular Slabs

The average difference in labour productivities between top and bottom layers fixed in non-rectangular slabs, i.e. Geom = 1, was quantified as follows:

Top Layer, LLoc = 1:

$$P(kg/mh) = 57.55 + 8.71(14.73) + 0.000871(9353.03) - 27.26(1) + 0.00157(1 * 9353.03) - 37.28(1) = 144.14$$

Bottom Layer, LLoc = 0:

$$P(kg/mh) = 57.55 + 8.71(13.39) + 0.000871(7454.35) - 27.26(1) + 0.00157(1 * 7454.35) - 37.28(0) = 165.11$$

Therefore, the average percentage difference was determined as shown in equation (11).

$$\left[\frac{(165.11 - 144.14)}{165.11}\right] * 100 = 12.70\% \qquad \text{Eq. 11}$$

On average, a loss in labour productivity of approximately 13%, in comparison with the bottom layer, is associated with fixing the top layer reinforcement of non-rectangular slabs.

Consistent with the results obtained from the macro-level observation analysis, Table 4 determines strong correlation and high determination coefficients between the buildability factors explored and labour productivity, i.e. 89.71% and 80.49% respectively. Moreover, Table 5 shows that all factors are significant in their impacts on labour productivity, i.e. p-value < 0.050, and that the influence of the rebar diameter remains the more influential of the two continuous factors on fixing labour productivity.

Discussion of Results and Implementation of Findings

This investigation has determined the effects and relative influence of buildability factors on rebar fixing labour productivity of beamless slabs. There are few published quantitative results, especially at this activity level, with which to compare the findings of this study, however, such data as exist have been examined and discussed.

Aldana (1991) and Hidayatalla (1992) concluded a positive relationship between rebar diameter and fixing labour productivity. The findings of this study at both levels; macro and, micro, further substantiate their findings. The quantified results show that as the rebar diameter increases by 1.00 mm, macro and micro-level average fixing labour productivity significantly increases by 7.43 kg/mh and 8.71 kg/mh, respectively.

This pattern can be explained by the rationale that, for the same quantity of reinforcement, as the rebar diameter increases, fewer number of reinforcing bars are fixed, hence resulting in higher labour productivity. Furthermore, since the fixing process comprises, mainly, placing and tying rebar in positions, tying reinforcement bars is a time consuming process, but it is approximately the same for tying thin or thick bars. As a result, within the same labour input, thick bars can be tied; thus fixing larger reinforcement quantity and therefore higher labour productivity is achieved.

However, this argument may be valid up to a certain point where the weight of a rebar becomes too great and physically stressful to allow a single fixer to lift and work with for a prolonged period of time, which may require two or more fixers to lift and place in position. Such a required increase in labour input, relative to the rebar diameter size being fixed, can reduce or even counterbalance the ratio of the quantity fixed to labour input, which can overshadow the positive effect gained from placing and tying large diameter size bars. In view of this discussion, strictly speaking, the pattern depicted in this investigation is valid for the rebar diameters observed, which ranged from a minimum of 8 mm to a maximum of 25 mm.

Hidayatalla (1992) concluded a negative relationship between high steel content and fixing labour productivity of slabs. His works quantified an average loss of 1.11 kg/mh in labour productivity as the steel content increases by 1.00 kg/m^3. However, other factors which simultaneously affect fixing labour productivity, e.g. geometry of slabs, location of reinforcement layer, and any possible related interaction amongst these factors, were not considered.

In contrast to the previous finding, this research determines a significant positive relationship between reinforcement quantity and fixing labour productivity; as the quantity of reinforcement fixed increases by 1.00 kg, macro and micro-level labour productivity, on average, increases by 0.000492 kg/mh and 0.000871 kg/mh, respectively.

The interaction effect between the reinforcement quantity and slab geometry reveals an interesting finding. The interaction coefficient term determines a significant increase in the intensity of the positive influence of reinforcement quantity on labour productivity of non-rectangular slabs, i.e. the positive influence of reinforcement quantity on labour productivity is greater in non-rectangular slabs, in comparison with rectangular slabs.

This finding may be related to the following two factors: (1) as the quantity of reinforcement increases in non-rectangular slabs, less variability of bar lengths is encountered by steel fixers to locate the “right” bar length, hence higher labour productivity is achieved; and (2) the positive effect of reinforcement quantity on labour productivity is stronger than the negative impact of the slab geometry, therefore, overshadowing its negative influence on the efficiency of the fixing operation.

The positive relationship between the reinforcement quantity and fixing labour productivity determined by this study may be further ascribed to the following reasons: (a) an initial contributory time is required by gang members to prepare work areas, work out rebar splicing locations and details, transport and distribute reinforcing steel bars prior to commencing the direct or effective work. Therefore, if an activity is of a small-scale type, a major portion of the macro-level total input is directed towards contributory rather than effective work; (b) the researcher noticed that a fixer would just as easily and within approximately the same time frame, place and tie for instance, similar number of 14 mm and 16 mm diameter bars, thus larger quantity and higher labour productivity; (c) when gang members are confronted with large scale activities, better preparation, planning and control is applied on sites; and (d) in large scale monitored activities, the researcher further observed that gang members tend to work harder and take less frequent breaks. In view of the preceding discussion, such an effect may be referred to as “economy of scale”.

The importance of applying the design rationalisation and standardisation concepts was the subject of several research projects (CIRIA 1999; Fischer and Tatum 1997; Dong 1996; Moore 1996a). Unlike rectangular slabs, where reinforcing steel bars are only of two different lengths, and in the special case of the square type where all bars have the same length, fixing reinforcement in non-rectangular slabs is associated with additional labour inputs directed toward searching for the “right” bar length amongst the variable stacked lengths. Therefore, standardising layout modules minimises waste of materials, improves the buildability of this activity, and enhances the productivity of the operation.

The investigation of the effect of slab geometry on labour productivity further corroborates the positive influence of these concepts on fixing labour productivity. The results obtained show that, in comparison with rectangular slabs, macro and micro-level fixing labour productivity, on average, decreases by 20.78 kg/mh and 27.26 kg/mh, respectively as a result of rebar fixing in non-rectangular slabs. Furthermore, on average, a loss of approximately 15% in fixing labour productivity, compared to rectangular slabs, is incurred due to rebar fixing in non-rectangular slabs.

Fischer and Tatum (1997) discussed the potential effect of reinforcement location on the buildability level of construction projects. However, their work was limited to design guidelines and recommendations geared towards buildability knowledge and improvement. This research explored the influence of reinforcement location in slabs and quantified the average difference in fixing labour productivity between bottom and top layers.

Fixing the top reinforcement layer in slabs is associated with a significant loss in labour productivity. Moreover, this pattern is consistent in both categories of slabs observed, rectangular and non-rectangular. In comparison with fixing bottom layer reinforcement, the results obtained determine an average labour productivity loss of approximately 15% and 13%, relative to fixing top layer reinforcement of rectangular and non-rectangular slabs, respectively.

This finding can be attributed to the following reasons. First, the mobility and motor skills of fixers are substantially reduced when tying top layer bars while standing on top of the reinforcement grid. Second, unlike fixing bottom layer reinforcement, top layer fixing operation involves lifting bars a distance approximately equal to the thickness of the slab prior to placing and tying bars in positions. Third, the additional labour input required to place the supporting chairs of the top layer reinforcement does not contribute to the measurement of the output, i.e. quantity of reinforcement fixed, hence lower fixing labour productivity is associated with this layer.

Notwithstanding that general buildability heuristic principles are available for designers, knowledge bases that support specific and timely buildability input to design decisions do not exist (Fischer and Tatum 1997). Consequently, such principles may be regarded as exhortations of good practice and common sense, often obtained using “Delphic Research Methods” (Cheetham and Lewis 2001). Furthermore, most of the existing recommendations and suggestions for buildability improvement, the researcher argues, lack the supporting quantitative evidences, which lend little reliability to the extent to which such recommendations influence the productivity of the construction process on the one hand, and are often associated with scepticism, especially amongst design practitioners, on the other.

Conversely, the quantitative results of this study are obtained through rigorous research and analysis, and thus can be used as supporting references for “formalizing” the specific buildability knowledge of this activity. However, since some recommendations, when implemented at the design level, may result in material increase, e.g. forms, reinforcement and/or concrete, designers should carefully evaluate the cost/benefit ratio before deciding on a specific option.

The effect of rebar diameter on labour efficiency suggests that structural designers should, for the same quantity of reinforcement required and within allowable limits under the prevailing code of practice, opt for specifying the largest possible rebar diameter. The effect of reinforcement quantity further suggests that any marginal increase in quantity, hence cost, as a result of specifying a larger rebar diameter, may be compensated by its positive influence on labour productivity.

Furthermore, architects should consider the negative influence of slab geometry on the fixing operation and take advantages of design rationalisation and standardisation concepts by keeping non-rectangular modules and bays to a minimum.

On the other hand, the patterns of results obtained may be further used by construction managers for effective activity planning, scheduling, resource levelling, and efficient labour utilisation.

Conclusions and Recommendations for Further Research

Due to the importance of in situ reinforced concrete material to the construction industry, this research focused on investigating and quantifying the effects and relative influence of buildability factors on the labour productivity of one of its major labour intensive trades; rebar fixing. Since beamless slabs are among the major activities, which are frequently encountered on construction sites, improving its rebar fixing labour productivity would help reducing the risk of labour costs overrun and increases the efficiency of the operation.

The effects of rebar diameter; reinforcement quantity; slab geometry; and reinforcement layer location, on fixing labour productivity of beamless slabs are determined and found to be statistically significant in their impacts at both levels observed; macro, and micro.

The findings of this study fill an important gap in quantitative buildability knowledge of this activity, which may be used to provide designers with feedback on how well their designs consider the requirements of buildability principles, and the tangible consequences of their decisions on site labour efficiency. In addition, practical recommendations are presented, which can improve the buildability level of this activity, hence translate into higher labour productivity and lower labour costs. Moreover, the depicted patterns of results may provide guidance to construction managers for effective activity planning and efficient labour utilization.

Although several findings have been drawn from this investigation, further similar research into the effects of buildability factors on rebar fixing, and other trades, i.e. formwork and concreting, labour productivity which are common to other structural members, is recommended. It is further recommended to investigate the range of rebar diameters, beyond 25 mm, within which the positive effect determined on fixing labour productivity, remains valid.

The results obtained, in addition to other trades and structural elements recommended for exploration, can ultimately be used to develop an automated “Buildability Design Support System”. Such a system would be useful for formalizing the specific buildability knowledge of in situ reinforced concrete construction, thus improving the performance of projects in an ever-increasing demand for faster and lower cost delivery of constructed facilities.

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