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Buildability Factors that Influence Micro-Level Formwork Labour Productivity of Beams in Building Floors

Abdulaziz M. Jarkas

Abstract: Buildability is one of the most important factors that influence labour productivity. Nevertheless, a thorough literature examination revealed a dearth of research concerning the effects of buildability on labour productivity of in situ reinforced concrete construction. Beams are major components of building floors, and the objective of this investigation is to explore the buildability factors that influence their micro-level formwork labour productivity. Therefore, a large volume of productivity data was collected and analysed using a categorical interaction-regression method. As a result, the main and interaction effects of beam repetition, size, intersections and span geometry were determined. The obtained results indicate that the investigated factors significantly influence the forming operation labour efficiency and substantiate the importance of applying design rationalisation, standardisation and repetition concepts to the design stage of construction projects. The findings satisfy the explored activity buildability knowledge gap, which can be used to provide designers with feedback on how well their designs consider the buildability principle requirements, as well as their decision consequences on the forming operation productivity.

Keywords: Buildability, Building Floors, Formwork, Labour productivity, Beams

INTRODUCTION

Construction is the world's largest and most challenging industry (Tucker, 1986). In 1997, the United States construction industry accounted for 10% of their gross domestic product (GDP) and employed over 10 million people, making the industry the largest in the country (Allmon et al., 2000). Nonetheless, the construction industry faces several problems and challenges, especially in developing countries, where such difficulties arise due to socioeconomic pressures, status quo complacency, resource shortages and the obsolescence of some statutes and codes (Ofori, 2006). Because construction is a labour intensive industry, concern over its labour productivity is clearly justified.

Executive Vice President - Projects
Al Mazaya Holding Co., KSCC, State of Kuwait
*Corresponding author: jarkas@mazayarealestate.com

The influence of buildability on construction processes has been the subject of numerous research projects, both in developed and developing countries (Lam and Wong, 2009; Saghatforoush et al., 2009; Lam et al., 2007; Pulaski and Horman, 2005; Nima et al., 2002; Carter, 1999; Williamson, 1999; Poh and Chen, 1998; Fischer and Tatum, 1997; Alshawi and Underwood, 1996; Dong, 1996; Hyde, 1996; Moore, 1996; Munshi, 1992; Griffith, 1987). However, only a few research endeavours were able to quantify such an influence in practical terms. Most of the reviewed literature introduced general, macro-level guidelines and recommendations, according to the potential influence of various variables on the productivity of the process. In one of the few textbooks that is entirely devoted to buildability, Ferguson (1989) identified a breadth of factors that must be considered to make a design buildable and provided many buildability problem examples and suggestions for improvements. However, while such suggestions allow the classification of buildability issues according to their detail level, the buildability issues are unable to be linked to the specific design decisions.

Several factors affect construction labour productivity; however, buildability is among the most significant (Horner et al., 1989). Buildability, as defined by the Construction Industry Research and Information Association (CIRIA), 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).

Design simplification is achieved through the implementation of the following three buildability principles: (1) rationalisation; (2) standardisation and (3) element repetition (Dong, 1996; Fischer and Tatum, 1997; Jarkas, 2005). 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, 1996).

Floor beams are the major components of most building floors, and due to the importance of formwork trade to in situ reinforced concrete construction, the objective of this research is to quantify the main and interaction effects of the following buildability factors on their micro-level formwork labour productivity: beam (1) size; (2) size repetition; (3) intersections and (4) span geometry.

This report begins with a brief overview of the formwork trade, presents a research method and analyses, provides a discussion of the obtained results and concludes with a set of recommendations that are marketed toward enhancing the design buildability level and improving the formwork labour productivity of the explored activity.

FORMWORK TRADE OVERVIEW

In the United States and in most countries, the cost of formwork ranges from one-third to two-thirds of the reinforced concrete frame total costs (Hurd, 2005; Illingworth, 2000). Consequently, formwork should be carefully handled and reused as many times as possible. Designers should aim to maximise the number of times that the form can be reused and minimise the form erection and striking times. In addition, dimension standardisation, design scheme rationalisation and element size repetition throughout the project are essential to ensure formwork material efficiency and cost-effective utilisation.

A wide variety of materials can be used for formwork, such as timber, steel, aluminium, glass fibre reinforced plastic (GRP) and a combination thereof. However, the most common material used is timber and is also known as “traditional” formwork (Brett, 1988). Timber has the advantage over all the other materials because it can be easily cut, handled and assembled on site. Timber is used as bearers in soffit forms and waling in wall forms. Plywood is primarily used for panels. Both traditional and proprietary formwork employ plywood, which is by far, the most common sheathing and soffit material used.

Based on the preceding discussion, it may be concluded that each type of the previously highlighted material is associated with its own task-level difficulty, which can also be an influential buildability factor that affects the forming operation labour efficiency.

Almost universally however, the most common material used in beam formwork is timber. The main tasks of this activity include setting out the soffit levels, where the levels are clearly marked on all the vertical-supporting members (i.e., columns and walls). When the levels are inspected and verified, the falsework begins to support the building floor formwork. When the floor formwork is ready to commence, a supporting frame that is composed of bearers and joists for beam soffits is first erected. The beam sides are placed in position and securely nailed into soffits upon the reduced level re-inspection of the soffits. Once the slab panel forming surfaces are placed and nailed into the beam sides and the reinforcement and electro-mechanical activities are completed and inspected, the formwork members return for final alignments, levelling, bracing and securing forms in positions. Concreting may then commence.

RESEARCH METHOD AND ANALYSES

This study focused on exploring the buildability factors that affect the micro-level formwork labour productivity of beams in building floors. Consequently, the observations that were targeted "effective" or "direct" labour inputs were used to achieve the activity. Therefore, sub-activities or contributory labour inputs, such as work area preparation and setting out and reading the plans that are of little influence at this level. The rational underlying such an approach was two-fold: (1) exploring the effects of buildability factors at the activity level would limit any interference of other, non-related, factors on labour productivity and (2) quantifying the factor influences at this level would assist in acquiring an in-depth understanding of the overall macro-level phenomena.

The related labour productivity data, which were part of a larger research project, were collected from thirty-nine 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 a nineteen-month period in which a total of 828 labour productivity indices [i.e., beam formwork area erected (m^2) per productive labour input (man-hour, mh)] at the activity level were quantified. Such a large data volume enabled valid, reliable and robust statistical results. The monitored projects included residential and office buildings, commercial centres, industrial facilities and warehouses.

Because several factors other than buildability affect labour productivity on construction sites (Jarkas, 2005; Horner et al., 1989), to further minimise such effects, construction sites sharing common features, such as a contract procurement method, geographical location and formwork erection method at the investigated activity level, were selected for observation. Moreover, all encountered delays during the forming operation were recorded and discounted, where only productive labour inputs were used to quantify the labour productivity indices. Notably, for all observed sites, timber formwork was used in the floor beam activities.

The investigated buildability factors included beam size, size repetition, intersections and span geometry. The beam size repetition factor is a qualitative variable and was thus classified into two categories: (1) first formed and (2) repeated formed beams. The beam sizes were represented by the actual formwork area used and were determined with equation 1.

$$[\,Beam\ side\,(m) * 2 + Soffit\ width\,(m)] * Beam\ span\,(m) \qquad (1)$$

The beam factor intersections were determined using the total number of joints that were formed in the beams as a result of such intersections, as depicted in Figure 1.

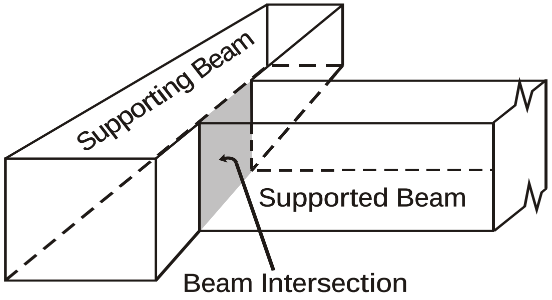

Figure 1. Formwork Joint at the Beam Intersection

For the beam repetition factor, the beam span geometry is a qualitative variable, which was further classified into the following two categories: (1) straight and (2) curved.

The investigated buildability factor main and interaction effects on the formwork labour productivity of the beams were analysed using a categorical interaction-regression method (Jaccard and Turrisi, 2003; Sincich et al., 2002; Gujarati, 1995; Hardy, 1993; Lawrence, 1992; Aiken and West, 1991; Sanford, 1985; Friedrich, 1982).

Because the repetition factor was classified into two different qualitative categories, a binary dummy variable, a value of 0 or 1 (e.g., 0 if the beam is first formed and 1 if the beam is repeated), was introduced into the regression model to quantify the average difference in labour productivity between the two categories. The coding however, was arbitrary and would be valid enough to code the first formed and repeated beams with 1 and 0, respectively.

Main effect 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 model variables are held constant. However, the effect of an independent variable on the dependent variable is dependent on the level or intensity of another model independent variable (Jaccard and Turrisi, 2003; Jaccard et al., 1990). 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 independent variables. A typical regression model that involves the interaction between the continuous and dummy variables possesses the basic form that is shown in equation 2 (Jaccard and Turrisi, 2003).

$$Y = b_0 + b_1 X_1 + b_2 D_2 + b_3 (X_1 * D_2), \tag{2}$$

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 of the relationship between the continuous independent variable, X_1, and the dependent variable, Y, for the two categories that are represented by D_2. Notably, we have shown that the most commonly encountered interaction in this model (i.e., interaction between the continuous and dummy variables) can occur between two continuous or two dummy variables. Moreover, a multiple regression model may involve several interaction terms.

Because regression models involve several independent variables that have different measurement units, a direct size comparison of various coefficients to assess their relative influence on the dependent variable (i.e., labour productivity) may be spurious. Therefore, before a meaningful investigation regarding the independent variable relative influence (i.e., buildability factors) can be conducted, the regression coefficients of the independent variables must be standardised (Kim and Feree, 1981). The standardised regression coefficients are then measured on the same scale with a mean of "0" and a standard deviation of "1". Thus, the coefficients are directly comparable to one another, and the largest coefficient correlates to the absolute value, indicating that the dependent variable exhibits the greatest influence.

The regression coefficient is standardised using equation 3.

$$b_k^{\,*} = b_k \left(\frac{s_k}{s_y} \right) \tag{3}$$

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. The standardised regression coefficients are commonly referred to as beta weights.

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

$$\text{Relative influence of the k}^{\text{th}}\text{ factor} = \frac{\text{Standardised coefficient value of k}^{\text{th}}\text{ factor}}{\text{Standardised coefficient value of the reference factor}} \quad (4)$$

Due to the complexity that is involved in the forming process and in comparison with straight beams, curved beams are associated with substantial additional labour input. Therefore, interaction terms were introduced and added to the model to unravel the effect of such complexity on the influence of other explored buildability factors, over and above their individual effects.

The relationship between labour productivity and the buildability factors at a 0.050 significance level was determined using the multiple categorical interaction-regression model shown in equation 5.

$$P(m^2/mh) = b_0 + b_1 RF + b_2 SA + b_3 NJ + b_4 GOS + b_5 (GOS * SA) + b_6 (GOS * NJ) + b_7 (GOS * RF) \quad (5)$$

where RF is a dummy variable, "repetition factor," of the beam observed and quantifies the average difference in labour productivity between the repeated and first formed beams. The repetition factor assumes the following two values: (1) 0, first formed beams and 1, repeated beams. SA (m^2) is the "shutter area" of the observed beam, NJ denotes the "number of joints" that are formed within the beam observed and GOS is a dummy variable, which represents the "geometry of span" of the observed beam and quantifies the average difference in the labour productivity between the curved and straight beam spans. As with the repetition factor, the span geometry is identified by the following two values: (1) 0, straight beam span and 1, curved.

The interaction terms, (GOS ***** SA) and (GOS ***** NJ), shown in equation 5 assume that the average rate of change [i.e., slope of the relationship between the shutter area (SA) and the number of beam joints formed (NJ)]. In contrast, the formwork labour productivity is different for the two categories that are represented by the dummy variable, GOS (i.e., straight vs. curved beams). The interaction term (GOS * RF) moreover, assumes a different repetition effect on the labour productivity for the two span geometry categories.

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

Table 1. Overall Regression Model Statistics for the Formwork Labour Productivity of Floor Beams

Correlation Coefficient (R)	94.91%
Coefficient of Determination (R^2)	90.08%
Standard Error	0.979
F(7,820)	1064.13
p-value	0.000
No. of Observations	828

Table 1 determines the strong correlation and high determination coefficients between the explored buildability factors and labour productivity, which were 94.91% and 90.08%, respectively. In addition, Table 2 shows that all buildability factors are significant in their effects on the formwork labour productivity (i.e., p-value, < 0.050). The interaction-regression model that represents the relationship between the formwork labour productivity and buildability factors was quantified by the regression model is shown in equation 6.

$$P(m^2/mh) = 5.46 + 1.43\,RF + 0.0831\,SA - 0.305\,NJ - 4.76\,GOS - 0.0691\,(GOS * SA) + 0.251\,(GOS * NJ) - 0.923\,(GOS * RF) \quad (6)$$

The total number of observations made for the floor beams activity was 828 of which 653 straight and 175 curved beams were monitored. Table 3 presents the average shutter areas and number of joints formed for the two observed beam categories.

Table 3. Average Buildability Factor Values that Influence the Formwork Labour Productivity of Straight and Curved Floor Beams

Span Geometry	Total No. of Observation	Average Shutter Area (m^2)	Average Number of Joints
Straight	653	18.49	0.95
Curved	175	10.05	0.99
Total	828	16.70	0.96

Table 2. Regression Coefficient Statistics for the Formwork Labour Productivity of Floor Beams

Coefficient	Value	Standard Error	p-value	VIF[1]	Standardised Coefficient Value	Influence Rank	Relative Influence
SA (m^2)	0.0831	0.00188	0.000	1.19	0.531	1	1.00
NJ	–0.305	0.0300	0.000	1.78	–0.149	2	0.28
RF	1.43	0.104	0.000	1.27	N/A[2]	N/A	N/A
GOS	–4.76	0.119	0.000	2.07	N/A[2]	N/A	N/A
(GOS * SA)	–0.0691	0.00690	0.000	1.81	N/A	N/A	N/A
(GOS * NJ)	0.251	0.0470	0.000	2.04	N/A	N/A	N/A

Notes:

[1] Variance inflation factor indicates the correlation among the independent buildability factors in the model.

[2] Dummy variables are used to quantify differences in levels between or among categories, therefore, the normal interpretation for standardised coefficients does not apply.

The interaction-regression model involves two qualitative dummy variables that quantify the effects of the formwork labour productivity repetition factor and span geometry on the average percentage labour productivity differences. Additionally, the repetition and span geometry forms were determined after substituting the corresponding continuous buildability factor average values, shown in Table 3, into equation 6 for each span geometry category and repetition form.

QUANTIFYING THE AVERAGE PERCENTAGE DIFFERENCE IN LABOUR PRODUCTIVITY DUE TO THE REPETETION EFFECT IN STRAIGHT BEAMS

The average labour productivity of the first and repeated formed straight beams, respectively, was quantified as shown below:

$$P(m^2/mh)=5.46+1.43(0)+0.0831(18.49)-0.305(0.95)-4.76(0)$$
$$-0.0691(0*18.46)+0.251(0*0.95)-0.923(0*0)=6.71$$

$$P(m^2/mh) = 5.46 + 1.43(1) + 0.0831(18.49) - 0.305(0.95) - 4.76(0) - 0.0691(0*18.49) + 0.251(0*0.95) - 0.923(0*1) = 8.14.$$

The average percentage difference in the labour productivity between the two repetition factor categories for the straight beams was therefore, determined as shown below:

$$\left[\frac{(8.14-6.71)}{6.71}\right]*100 = 21.31\%.$$

Accordingly, a 21% gain in formwork labour productivity was achieved as a result of the straight beam form repetition.

QUANTIFYING THE AVERAGE PERCENTAGE DIFFERENCE IN LABOUR PRODUCTIVITY DUE TO THE REPETETION EFFECT IN CURVED BEAMS

Similarly, the average labour productivity of the first and repeated formed curved beams, respectively, was determined as shown below.

$$P(m^2/mh) = 5.46 + 1.43(0) + 0.0831(10.05) - 0.305(0.99) - 4.76(1) - 0.0691(1*10.05) + 0.251(1*0.99) - 0.923(1*0) = 0.79$$

$$P(m^2/mh) = 5.46 + 1.43(1) + 0.0831(10.05) - 0.305(0.99) - 4.76(1) - 0.0691(1*10.05) + 0.251(1*0.99) - 0.923(1*1) = 1.29.$$

Therefore, the average percentage difference in the labour productivity between the two repetition factor categories for curved beams was quantified as follows:

$$\left[\frac{(1.29-0.79)}{0.79}\right]*100 = 63.30\%.$$

A 63% formwork labour productivity gain was achieved as a result of the repetition forms in the curved beams.

QUANTIFYING THE AVERAGE PERCENTAGE DIFFERENCE IN LABOUR PRODUCTIVITY DUE TO THE SPAN GEOMETRY IN FIRST FORMED BEAMS

The average labour productivity of the first formed straight and curved beams, respectively, was quantified as follows:

$$P(m^2/mh)=5.46+1.43(0)+0.0831(18.49)-0.305(0.95)-4.76(0)$$
$$-0.0691(0*18.49)+0.251(0*0.95)-0.923(0*0)=6.71$$

$$P(m^2/mh)=5.46+1.43(0)+0.0831(10.05)-0.305(0.99)-4.76(1)$$
$$-0.0691(1*10.05)+0.251(1*0.99)-0.923(1*0)=0.79.$$

The average percentage difference in the formwork labour productivity between the first formed curved and straight beams was determined as shown below.

$$\left[\frac{(6.71-0.79)}{6.71}\right]*100=88.23\%$$

For the first formed beams, in comparison with the straight type, an average percentage loss of approximately 88% in the labour productivity was associated with the forming curved beams.

QUANTIFYING THE AVERAGE PERCENTAGE DIFFERENCE IN LABOUR PRODUCTIVITY DUE TO THE SPAN GEOMETRY IN REPEATED FORMED BEAMS

The average labour productivity of repeated formed straight and curved beams, respectively, was determined as follows:

$$P(m^2/mh)=5.46+1.43(1)+0.0831(18.46)-0.305(0.95)-4.76(0)$$
$$-0.0691(0*18.46)+0.251(0*0.95)-0.923(0*1)=8.13$$

$$P(m^2/mh)=5.46+1.43(1)+0.0831(10.05)-0.305(0.99)-4.76(1)$$
$$-0.0691(1*10.05)+0.251(1*0.99)-0.923(1*1)=1.29.$$

The average percentage difference in formwork labour productivity between the repeated formed curved and straight beams was quantified as shown below.

$$\left[\frac{(8.13-1.29)}{8.13}\right]*100=84.13\%.$$

For the repeated forms category, an average percentage loss of approximately 84% in labour productivity was associated with forming curved beams when compared with straight beams.

The difference in the average percentage loss between the curved and straight formwork labour productivity of beams for the two forms repetition categories was only 4%. This difference indicated almost a consistency in the average percentage loss in formwork labour productivity due to span geometry. Such a modicum difference further confirms the complexity that is associated with forming curved beams, as compared with straight beam spans.

DISCUSSION OF RESULTS AND PRACTICAL IMPLEMENTATION OF FINDINGS

Smith and Hanna (1993) hypothesised that similar buildability factors positively influence formwork labour productivity. Such factors included simplicity, standardisation and element repetition. The findings of this research not only proved such hypotheses, but also quantified their effects on the formwork labour productivity of beams in building floors.

Several previous reports discussed the importance of repetition on construction productivity (CIRIA, 1999; Fischer and Tatum, 1997; UOTS, 1997; Dong, 1996; Moore, 1996; Ferguson, 1989; O'Connor et al., 1987). In this study, the effect of material repetition on beam formwork labour productivity was quantified. On average, the positive difference in labour productivity between the repeated and first formed straight beams was 1.43 m^2/mh. In addition, an average 21% and 63% gain in labour productivity was achieved using repeated straight and curved beams, respectively, as compared with first formed beams. Such a difference in labour productivity gain between curved and straight beams was related to the substantial additional labour inputs that were associated with the measuring, setting out, cutting and assembling of curved beam soffits and sides, which are significantly saved as a result of size repetition.

Although the author could not find similar research with which to correlate this finding, the outcome further substantiates the positive influence of repetition on the activity labour efficiency.

The obtained result showed that labour productivity increases, on average, by 0.0831 m^2/mh, as the straight beam shutter area increases by 1.00 m^2. In addition, as shown in Table 2, between the two continuous explored buildability factors, the size effect is more influential towards its positive impact on formwork labour productivity. Thus, the implementation of the design rationalisation concept by substituting a fewer number of small beam sizes that are larger in size in the floors can positively affect the forming operation efficiency.

The obtained size effect results in this study may be attributed to the following: (1) when members are confronted with large scale activities, better preparation, planning and control is applied on sites; (2) in large scale monitored activities, members tend to work harder and take less frequent breaks and (3) it approximately requires the same labour inputs to form 300 mm x 500 mm cross sectional beam as for 300 mm x 600 mm due to the same span length. In view of the preceding discussion, such an effect may be referred to as "economy of scale", which is further augmented by the design rationalisation and standardisation concepts.

The negative effect of beam formwork interruption was revealed after investigating the beams intersection impact on labour productivity. The study showed that labour efficiency decreases, on average, by 0.305 m^2/mh, as the number of formed joints in the straight beams increases by one unit. This finding was ascribed to the additional labour inputs that were required for measuring, cutting and fixing the beam sides at such intersections.

Nevertheless, the author could not identify relevant previous research to compare the quantified effect of the beam joints formed on labour productivity. This finding further falls within the rationalisation and standardisation concepts that were advocated in previous studies (Azuma et al., 2007; Fischer and Tatum, 1997; UOTS, 1997; Dong, 1996; O'Connor et al., 1987).

Previous research (Smith et al., 1993; Ferguson, 1989) attributed poor buildability to curved forms. This investigation not only corroborated this concept, but also quantified its influence on the forming operation efficiency. The related outcome showed, on average, a 4.76 m^2/mh loss in labour productivity between curved and straight beams. Furthermore and in comparison with straight beams, for first and repeated shuttered curved beams, an average loss of approximately 88% and 84%, respectively, in formwork labour productivity was incurred.

The interaction term between the beam span geometry and shutter area indicated a significant average reduction of 0.0691 m^2/mh in the relationship slope of the beam shutter area and labour productivity for the two monitored span geometry categories, curved and straight beams. This finding may be related to the complexity that is associated with the shuttering of curved beams and hence, reflected through the reduction in the positive influence intensity of the beam shutter area on the formwork labour productivity.

Contrary to the previously discussed effect, the interaction between the beam span geometry and joint number of joints revealed a significant increase of 0.251 m^2/mh in the relationship slope of labour productivity and the number of joints formed for the two span geometry categories (i.e., a decrease in the influence negative intensity of the beam joint number on labour productivity was observed). This significant positive shift in the slope may be explained by the fact that as the joint number in curved beams increases, the effective curved beam span and thus, curved formwork, decreases. Thus, it becomes easier for carpenters to handle, bend and fix fibreboard beam sides in place to the required, but shorter, arc-lengths.

Contrastingly, the interaction term between the span geometry and repetition factor quantifies the average difference in labour productivity between curved repeated beams and first formed straight beams. The negative sign indicated that the curved beam labour productivity, even with the repeated forms and on average, is significantly lower, 0.923 m^2/mh, than that of the first formed straight beams.

Notwithstanding that general buildability recommendations and guidelines 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 general guidelines and suggestions for buildability improvement can be regarded as exhortations of good practice and common sense and often obtained using “Delphic Research Methods” (Cheetham and Lewis, 2001). Conversely, the outcomes of this investigation provide practical guidelines and recommendations for buildability improvement based upon quantified results that were obtained through rigorous research and analyses and hence, can be useful for “formalising” the specific buildability knowledge of the investigated activity.

The recommendations provided in this paper may be used by designers who seek to optimise the buildability of their own designs and enhance the forming operation labour efficiency, particularly in developing countries where 75% of the global construction workforce is located (CICA, 2000). However, when implemented, some recommendations may result in material increase (e.g., forms, reinforcement and/or concrete). Therefore, designers should carefully evaluate their cost/benefit ratio before selecting a specific option.

These outcomes suggest that designers apply the following basic buildability principles to the construction project design stage: rationalisation; standardisation and repetition. Application of the repetition principle involves repeating building floor layouts, both architecturally and structurally. The formwork members can then achieve significant savings in measurements, setting out, cutting and forming floor beams labour inputs, which translate into an efficient and cost-effective forming operation. Applying the design rationalisation and standardisation concepts to the explored activity may be further achieved through minimising the beam number by using fewer beams that possess larger cross sections within the building floor. Moreover, the number of the forming joints at beam intersections may be avoided by employing framing beams onto the columns and walls. In contrast, architects should rationalise the curved or irregular modules in floor bays, which may lead to curved beams and thus, negatively impact the forming operation labour productivity.

CONCLUSIONS

Due to the significance of in situ reinforced concrete material in the construction industry, this research focused on investigating and quantifying the buildability factors that influence labour productivity of formwork, a major construction trade. Because beams are major and labour intensive, improving the building floor activity labour productivity would help reduce the risk of overrun labour costs and enhances operation efficiency.

The main and interaction effects of beam repetition, size, intersections and span geometry in building floors were determined and found to be significant in influencing micro-level formwork labour productivity. The obtained results not only corroborate the importance of applying rationalisation, standardisation and repetition principles to the design stage of construction projects, but also substantiate the positive impact of the "economy of scale" concept, which is further augmented by the application of these principles toward forming operation productivity.

There is widespread consensus that design is becoming increasingly significant in determining competitiveness. Therefore, these micro-level study findings satisfy an important gap in the buildability knowledge, which can be made readily available to designers for a related design decision and provide thorough and profound insight of the overall phenomena that affect their activity at the macro-level. In addition, the outcomes can be used to provide designers with feedback on how well their beam designs consider the buildability principle requirements and on their decision consequences on the formwork operation labour efficiency. Moreover the depicted result patterns may provide guidance to construction managers regarding effective activity planning and efficient labour utilisation.

Contrastingly, practical recommendations based on the findings of this investigation were presented. Upon implementation, these recommendations may enhance the explored activity buildability level, translating to higher labour productivity and lower labour costs, thus improving the project performances in an environment of ever-increasing demand for faster and lower cost delivery of finished buildings.

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