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THE IMPACTS OF BUILDABILITY FACTORS ON FORMWORK LABOUR PRODUCTIVITY OF COLUMNS

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Abstract. The impacts of buildability on formwork labour productivity of major in situ reinforced concrete elements such as, foundations, walls, columns, beams and slabs, are yet to be determined and quantified. The labour unit cost of columns formwork, in comparison with other constituents of the reinforced concrete frame, is constantly higher due to the forming complexity of these elements, especially non-rectangular shapes, and the small output achieved in the operation. Therefore, the objective of this research is to investigate the impacts of buildability factors on columns formwork labour productivity. To achieve this objective, a large volume of productivity data was collected and analyzed using the categorical-regression method. As a result, the impacts of the grid patterns, variability of column sizes, repetition, total and average shutter size, and geometry of columns are quantified. Apart from the variability of column sizes, the findings show significant effects of these factors on labour productivity, which can be used to provide designers feedback on how well their designs consider the requirements of buildability principles, and the consequences of their decisions on labour efficiency. Moreover, the depicted patterns of results may provide guidance to construction managers for effective activity planning and efficient labour utilization.

Keywords: buildability, categorical-regression, columns, formwork, labour productivity, rationalization, repetition, standardization.

1. Introduction

Construction is the world's largest and most challenging industry (Tucker 1986). On average, it contributes one-half of the gross capital and 3 to 8% of the Gross Domestic Product (GDP) in most countries (Arditi and Mochtar 2000). On the other hand, Horner *et al.* (1989) indicated that a 10% increase in construction labour productivity would yield annual savings of about £1 Billion to the British economy; a similar conclusion was echoed by Stoeckeel and Quirke (1992).

Several factors affect labour productivity, but buildability is among the most important (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).

Numerous previous studies investigated the effect of buildability on the construction process. However, a thorough examination of the literature revealed a dearth of research into the influence of buildability on labour productivity, especially at the activity levels, of an integral trade of in situ reinforced concrete material; namely, formwork.

The impacts of buildability factors on formwork labour productivity of major activities such as, foundations, columns, walls, beams and slabs, which in situ reinforced concrete structures are composed of, are yet to be determined in measurable terms.

In the United States, as the case with most countries, the cost of formwork trade ranges from one-third to two-thirds of the overall cost of the reinforced concrete frame (Hurd 2005; Illingworth 2000), of which, the cost of labours comprises approximately thirty percent (McTague and Jergeas 2002). Since formwork is a labour intensive trade, it may be argued that manpower is the only productive resource, thus construction productivity is mainly dependent upon human effort and performance. Consequently, investigating the effect of buildability factors on formwork labour productivity warrants the importance of this research.

Columns are among the major structural elements of reinforced concrete frames. In comparison with other members however, e.g., foundations, slabs on grade, and suspended slabs, the labour unit cost of columns formwork is constantly higher due to the forming complexity associated with these elements, especially in forming non-rectangular shapes on the one hand, and the small output achieved, i.e., square meters of formwork erected, on the other.

Therefore, the objective of this investigation is to determine the effects and relative influence of the following buildability factors on column formwork labour productivity: 1) grid pattern arrangement; 2) variability of column sizes; 3) repetition of sizes; 4) column sizes; and

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5) column geometry, consequently, labour productivity, hence labour cost, can be estimated for the various buildability levels of this activity both, reliably and with reasonable accuracy, which can enhance the competitiveness level of construction companies (Siskina *et al.* 2009).

In order to develop an understanding of the previous research that had been conducted and the progress developed in the area of buildability to date, this paper starts with a relevant literature review of topics related to this study, briefly introduces an overview of the formwork trade, presents the research method and analysis, provides a discussion of the results obtained, and concludes with recommendations primarily geared toward encouraging further investigations into the area of buildability; the most important of which, pertains to exploring its effects on other major elements of in situ reinforced concrete structures.

2. Literature review

The origin of the word productivity can be traced back to 1766 when it was first mentioned in an article by Quesnay (Sumanth 1985). More than a century later, in 1883, Littre defined productivity as the "faculty to produce", that is, the desire to produce. In the early twentieth century, a more precise definition, the relationship between output and the means employed to produce that output, was developed. In 1950, the Organization for European Economic Cooperation (OEEC) introduced a more formal definition of productivity: "productivity is the quotient obtained by dividing output by one of the factors of production. In this way, it is possible to speak of the productivity of capital, investment or raw materials according to whether output is being considered in relation to capital, investment or raw materials" (Sumanth 1985).

The US Department of Commerce defines productivity as Dollars of output per person-hour of labour input (Adrian 1987). Peles (1987) interpreted productivity as "the performance accomplished by operatives". Handa and Adballa (1998) on the other hand, defined productivity as "the ratio of outputs of goods and/or services to inputs of basic resources, e.g., labour, capital, technology, materials and energy". Arditi and Mochtar (2000) referred to productivity as "the ratio between total outputs expressed in Dollars and total inputs expressed in Dollars as well", whereas Horner and Duff (2001) expressed productivity as "how much is produced per unit input".

Based on the preceding discussion, it is obvious that the general consensus to define productivity is the ratio of output to input. Consequently, construction productivity can be regarded as a measure of outputs which are obtained by a combination of inputs. In view of this, two measures of construction productivity emerge: a) total factor productivity, where outputs and all inputs are considered; and b) partial factor productivity, often referred to as single factor productivity, where outputs and single or selected inputs are considered (Rakhra 1991; Talhouni 1990).

Depending on the research or industry estimate objectives, inputs may be measured in three different ways: 1) total time; 2) available time; and 3) productive time (Herbsman and Ellis 1990). Total time is defined as the total paid time, which is mainly used for estimation purposes. Available time is the total time minus "unavoidable" delays. Unavoidable delays include paid breaks and inclement weather. Available time is mainly used to measure management performance. Productive time is the available time minus "avoidable" delays. Avoidable delays are the results of inefficient site management practices, e.g., poor site coordination, sequencing problems, lack of materials, and instruction delays. Productive time is used to measure the skills and capabilities of the labour force and the impact of buildability on the construction process.

The advantages of the single factor productivity, e.g., labour productivity, are many. By focusing on a selected factor, the measurement process becomes easier and more controllable. As a result, reliable and accurate data can be collected. The complex nature of the construction process and the interaction of its activities, make the labour productivity measure the popular option, especially for researchers, since effective control systems monitor each input separately.

Several factors affect labour productivity, e.g., skill of operatives, quality of supervision, work methods, inaccurate drawings, rework, lack of materials, power tools and equipment, length of the working day, site layout, congestion and overmanning, proportion of work subcontracted, poor communication, interruptions, disruptions, and absenteeism; nevertheless, buildability remains among the most important (Adams 1989; Alinaitwe *et al.* 2007; Hanna *et al.* 2007; Horner *et al.* 1989; Watkins *et al.* 2009).

The word buildability, appears to have first entered the language in the late 1970s (Cheetham and Lewis 2001). An early attempt to address buildability can be credited to Sir Harold Emmerson (1962) when he suggested a new form of relationship between designers and constructors. The point of concern was the lack of cohesion between designers and constructors and the inability of both parties to see the whole construction process through each other's eyes.

In an exploratory report, "Buildability: an assessment", published in 1983 by the Construction Industry Research and Information Association (CIRIA), buildability was tentatively defined, and perhaps it is the most widely accepted definition, as: "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building" (CIRIA 1983).

In attempts to enhance the understanding of the buildability concept, many researchers elaborated on the definition in their work. Illingworth (1984) stated that the British construction industry would only be able to equal the efficiency of its global competitors by studying, and acting upon the requirements of buildability.

Ferguson (1989) defined buildability as the ability to construct a building efficiently, economically, and to agreed quality levels from its constituent materials, components, and sub-assemblies. Griffith (1987) suggested a compromise between consciously making the design more buildable and accommodating the many factors imparting an influence upon design including quality, aesthetics, time, and cost.

Hyde (1996) on the other hand, stated that the definition of buildability lacks precision when placed into operation in the design environment, and concluded that, buildability is not an absolute goal or quality as has been identified by many researchers, rather it is related to qualitative aspects of buildings and the level of complexity involved in the process. Therefore, a clear direction or modus operandi must be developed for buildability assessment, and that the knowledge should progress from operational principles to designers to achieve the buildability level desired.

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).

The first attempt to measure the influence of design on buildability was undertaken by the Building Research Station (BRS 1970). The operation of cranes on various construction sites was examined, and was concluded that "if the site layout, or the type of construction utilized make the crane operation difficult, then the whole construction process would be difficult and uneconomical". However, such an attempt failed to quantify the difficulty level associated with the site layout or type of construction.

Another attempt by the Royal Institution of Chartered Surveyors was a comparison between construction operations of the UK and the US, with emphasis on design and contractual procedures (RICS 1979). They concluded that "design cannot be divorced from construction without major time and cost penalties". Once again, the magnitude of such time and cost penalties was not determined.

The Construction Industry Research and Information Association (CIRIA) program of research, identified a constraint for achieving good buildability by stating that "the achievement of good buildability depends on both designers and builders being able to see the whole construction process through each other's eyes" (CIRIA 1983). Having identified this constraint however, no suggestion on how to assess or measure the achievement of good buildability was provided.

O'Connor *et al.* (1987) and Alshawi and Underwood (1993) discussed the negative effect of the variability of element sizes on the complexity of the construction process. However, their work comprised general guidelines without any quantification of the effects of such factors on the productivity of the related construction activities. Furthermore, Fischer and Tatum (1997) identified critical design variables which are important for the buildability of structures. Such variables included dimensions and details of elements; nonetheless, the impacts of such variables on labour productivity were not quantified.

Jergeas and Put (2001) in a study to identify the most significant gaps between the potential benefits of applying buildability principles to Alberta, Canada, concluded that buildability enhancement requires a collaborative industry effort which should focus on areas where the largest gaps currently exist between potential and realized benefits. These include the involvement of construction expertise during the design stage, and building mutual trust, respect, and credibility between project planners, designers, and constructors. Yet, another recommendation of good practice without any specific suggestion on how to assess, measure, or realize the potential benefits of applying the buildability principles tangibly.

Even though seminal work has been developed, in none of the mentioned examples, were there any quantified or quoted figures, or even a suggestion on how to measure the influence of buildability upon construction activities. Moreover, previous research did not provide specific guidance on how to assess or determine 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.

However, some previous research showed, quantitatively, the influence of buildability on labour productivity. Munshi (1992) explored the effects of geometry and openings configurations of block wall panels and, in comparison with plain walls, determined a significant average loss in labour productivity associated with constructing corners and openings. Williamson (1999) further investigated the relationship between design complexity and construction productivity. The level of design complexity was quantified as a factor of the total number of features observed in block wall panels such as, number of corners, openings, junctions, and terminations, and concluded that "an increase in design complexity increases the task-level difficulty, therefore, resulting in reduction in labour productivity".

Smith *et al.* (1993) reported a substantial loss of productivity ranging in ratio from 1.10 to 2.00 in comparison with straight walls base rate due to the presence of corners in wall perimeters, which further corroborated the patterns obtained by Smith and Hanna (1993).

Dong (1996) evaluated the effects of design on buildability, and concluded that design simplification is achieved through the implementation of the following three buildability principles: a) rationalization; b) standardization; and c) repetition.

Design rationalization is defined as "the minimization of the number of materials, sizes, components or subassemblies", whereas standardization is "a design philosophy requiring the designed product to be produced from those materials, components and sub-assemblies remaining after design rationalization has taken place" (Moore 1996). The design repetition concept involves repeating bay layout, floor grids, dimensions of elements, and storey height. On the one hand, repetition cuts the cost of construction through the re-use of forms, thus results in substantial saving in labour inputs used for setting-out, measurements and cuttings, and makes the labour force progressively more familiar with the site conditions and the sequence of operation, on the other.

In a comparison study between the construction labour cost of cast in situ and precast concrete slabs, Carter (1999) showed that the latter was less expensive per unit floor area than the former. Such a finding was further corroborated by Lam *et al.* (2007), where the precast method was rated as the most buildable construction method. Moreover, studies in the United States, United Kingdom, and Australia have demonstrated that improved buildability has lead to significant savings in both time and cost required for completing construction projects (Trigunarsyah 2004).

Nonetheless, the majority of previous research discussed the effect of buildability on a global basis overlooking an important aspect of the current problem. A practical solution to the problem, especially in reinforced concrete construction, the researcher argues, can be achieved through: 1) investigating and determining the effects and relative influence of buildability factors at the activity levels, i.e., foundations, columns, walls, beams, and slabs, which support and make up the building frame, so that the impacts of the overall phenomenon of buildability can be well understood and established, hence can be implemented with sufficient ease; and 2) quantifying such effects in measurable terms so that the tangible benefits of buildability principles may be realized and ultimately, formalized.

3. Formwork Trade Overview

Formwork is used to obtain a shape in concrete. It includes the actual material in contact with concrete and all the necessary associated supporting structures. Formwork is removed in a process called striking or stripping.

Formwork types are grouped according to their application as follows (Ricouard 1982): a) vertical formwork, where the concrete lateral pressure is the governing factor. Examples of this type involve columns and walls; and b) horizontal formwork, where the weight of concrete is the governing factor. Suspended slabs, decks, and cantilever structures are prime examples of this type.

A wide variety of materials is used for formwork, e.g., timber, hardboard, steel, aluminium, glass fiber reinforced plastic (GRP), and a combination thereof. The most common material however is timber, also known as “traditional” formwork (Brett 1988). Timber has the advantage over all other materials, especially in low to medium-rise buildings, because it can be easily cut, handled, and assembled on site, however, may not be the most economical option if a high finishing quality is required and a high degree of repetition is involved, where the advantages of the metal and plastic types prevail (Peurifoy *et al.* 2006). Timber is used as bearers in soffit forms as well as waling in wall forms. Plywood is mainly used for panels. Both traditional and proprietary formwork use plywood, which is by far, the most common sheathing and soffit material used.

In view of the aforementioned discussion, it may be concluded that each type of the previously presented materials is associated with its own task-level difficulty, hence can be also an influential buildability factor upon the labour efficiency of the formwork operation. However, since the majority of construction sites, which were available for observation at the data collection phase of this research, used the traditional formwork material in columns “shuttering”, this investigation focuses on this type of formwork.

Formwork is expensive. Therefore, it should be carefully handled and reused as many times as possible. In addition, standardization of dimensions, rationalization of design schemes, and repetition of element sizes throughout the project are essential to ensure efficient and cost-effective utilization of formwork materials.

Generally, the major tasks of columns formwork erections on sites include, axes lay-out, measuring, sides assembling, applying surface anti-adhesive material on inner plywood sides, which shall be in direct contact with the fresh, and subsequently hardened concrete, for ease of stripping, and to avoid damaging the concrete surface, especially column corners, placing sides in positions, plumbing, securing, and bracing in place. Commonly, columns vary in size and shape within projects, thus, unless otherwise contractually specified, on site assembled timber boards to the required size and shape are usually used in the shuttering process. The logic behind using timber boards is twofold. On the one hand, it minimizes wastage in plywood sheets, and provides flexibility in adjusting the size of columns between or among stories, on the other. When, for instance, the column size changes between two stories, rather than cutting and wasting expensive plywood sheets to adjust the size, sides of columns made of assembled timber boards can be easily adjusted by simply striking one or more of the boards and reassembling them to the required dimension. As a result, minimum damage to timber boards, if any, is experienced in this process, and these boards can be reused within the same or different sites.

4. Research Method and Analysis

The labour productivity data were collected at both levels; macro, and micro. Macro-level observation involved monitoring the overall activity within the trade, where the total productive labour inputs associated with completing the overall activity was recorded, therefore, a single labour productivity index was achieved, i.e., total area of formwork erected per total productive man-hours used to complete the activity. Labour inputs collected at this level included both; contributory time, i.e., time spent in setting-out, preparing work areas, transporting and distributing forms within the jobsite, reading plans, identifying elements locations, applying anti-adhesive material on plywood forms, measuring, and when required, cutting, as well as, direct or effective forming time used in sides assembling, placing in positions, plumbing, securing and bracing in place (Chan and Kumaraswamy 1995; Jarkas 2005). Micro-level observation on the other hand, focused on the direct observation of selected elements within the activity, therefore, the contributory time had negligible influence at this level of observation, where only direct productive forming labour inputs were used to quantify 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 can further provide a better understanding of the overall phenomena and findings of the explored factors affecting the activity; and 2) the impacts of other, non-buildability factors, e.g., sequencing problems, communication complexity, and site layout, on labour productivity are minimized at this level of observation.

Since several factors, other than buildability, influence labour productivity on sites (Horner *et al.* 1989; Jarkas 2005), the focus was on construction projects which shared common features such as, contract procurement method, geographical locations, and to a large extent, construction methods, but 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 level, thus their influence may not be best revealed. Moreover, in all sites observed, the forming process of columns, regardless of the project's type, was basically identical.

The differences in management procedures applied among the various types and magnitudes of sites monitored, at the project level, on the other hand, have little effect at the activity level of observation, whereas, the possible impacts of other interfering factors such as, size and composition of formwork crews, skill of operatives, motivation, 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 centers; and industrial facilities, ranging from a minimum of one, to a maximum of eight floors in height.

In an effort to minimize the negative influence of interruptions and disruptions on labour productivity, major encountered delays during the forming process, e.g., material shortage, unavailability of tools, accidents, and inclement weather, were recorded and discounted from the total labour inputs, thus only productive labour inputs were used to quantify the labour productivity indices, that is, area of formwork erected (m^2)/productive labour inputs (man-hours).

The formwork labour productivity data of this activity, 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 material is the prevailing type of construction. The data collection duration spanned a period of nineteen months, in which, a total of 182 and 736 labour productivity indices 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 columns observed were collected using the intermittent and direct observation techniques, respectively (Jarkas 2005; Munshi 1992; Noor 1992). Specifically designed data collection forms were used in all sites monitored to systematically and consistently record the essential productivity parameters of the labour inputs for the various columns observed, and to record major delays encountered during the forming process. The intermittent observation technique involved collecting macro-level labour inputs upon the completion of the activity, yet conducting occasional site visits during the forming operation to ensure that data collection forms are filled out regularly, and assess the physical progress of activities under observation. The direct observation method on the other hand, focused on pre-selected elements, which are usually completed within the same day, or during the progress of the activity. Therefore, micro-level labour inputs were, largely, collected on daily basis.

The data collected from crew leaders were cross-checked by both; superintendents, and site foremen for verification and accuracy. Moreover, elements monitored were visually inspected and marked on related drawings for output measurements.

The buildability factors explored, which are common to columns formwork activity included: grid patterns, i.e., the ratio of the total number of columns to the total number of column axes origins; variability of column sizes; repetition of sizes; column sizes; and geometry. In order to unravel the influence of column sizes on the macro-level labour productivity, this factor was further broken down into two levels: total size; and average size. The total size of columns observed was represented by the total formwork area used, that is, the total sum of shutter areas of individual columns contained within the activity, whereas the average size was quantified by dividing the total size of columns by the total number of columns within the activity. Total and average shutter areas (*TSA* and *ASA*) of rectangular and circular columns monitored were quantified mathematically as shown in Equations 1 (a and b), and 2, respectively.

Rectangular Columns:

$$TSA\ (\mathrm{m}^2) = \Sigma(Width\ (\mathrm{m})*2 + Length\ (\mathrm{m})*2)*Height\ (\mathrm{m}). \quad (1\ a)$$

Circular Columns:

$$TSA\ (\mathrm{m}^2) = \Sigma\ (\pi * (Radius\ (\mathrm{m}))^2) * Height\ (\mathrm{m}). \quad (1\ b)$$

$$ASA(\mathrm{m}^2) = \frac{Total\ shutter\ area\ of\ columns\ (\mathrm{m}^2)}{Total\ number\ of\ columns}. \quad (2)$$

The grid patterns or axes layout factor (*ALO*), as depicted in Fig. 1, was determined by the mathematical relationship shown in Eq. (3).

$$ALO = \frac{Total\ number\ of\ columns}{Total\ number\ of\ column\ axes\ origins}. \quad (3)$$

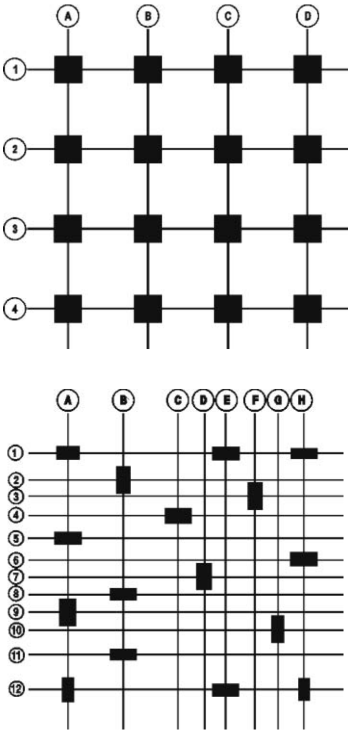

Fig. 1. Uniform and Symmetrical versus Scattered and Irregular Grids

It is important to note however that the concept of the grid pattern complexity illustrated in Fig. 1, remains valid for the column axes arrangement of any building shape which may be encountered, square, rectangular, trapezoidal, triangular, cylindrical, among other geometries.

The variability of sizes was represented by the total number of different column sizes encountered in the activity, whereas the size repetition factor was classified into two categorical variables: first; and repeated shutter.

In almost all sites observed, the majority of columns encountered were of the rectangular and circular types. Therefore, the exploration of the effect of column geometry on labour productivity was limited to these two shapes. The presence of circular columns at the macro-level observation was expressed by the percentage of circular columns (*PCC*) contained within the activity, and quantified as shown in Eq. (4).

$$PCC = \frac{Total\ shutter\ area\ of\ circular\ columns\,(\mathrm{m}^2)}{Total\ shutter\ area\ of\ all\ columns\,(\mathrm{m}^2)} \times 100. \qquad (4)$$

As previously explained, the micro-level observation focused on selected individual elements within the activity at the forming stage. Therefore, time spent in setting-out, preparing work areas, transporting, stacking, distributing forms within the jobsite, reading plans, identifying elements locations, measuring, and cutting, are of little influence on the productivity of the process at this level of observation. In view of this, buildability factors explored at the micro level were limited to column size and geometry.

As with the macro-level observation, the column size factor at the micro-level, was quantified using Eq. (1) (a and b), whereas the effect of column geometry was classified into two categories; rectangular, and circular.

It is to be noted that in all sites observed, the maximum difference in height among columns was approximately 1.00 meter. Therefore, the impact of this buildability factor, which can also be influential in its effect on formwork labour productivity, could not be determined, hence was discarded from the investigation.

Labour inputs collected were screened for possible measurement errors or outliers, an unusual observation which lies outside the range of the data values. The labour productivity indices for the elements observed were then quantified as shown in Eq. (5).

$$Labour\ productivity\,(\mathrm{m}^2/\mathrm{mh}) = \frac{Area\ of\ \ formwork\ erected\ \ (\mathrm{m}^2)}{Labour\ \ input\,(man\text{-}hours)}. \qquad (5)$$

The screened data were entered into a spreadsheet where the regression analyses were conducted, at 0.050 significance level, 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.

The effects and relative influence of the buildability factors on labour productivity were analyzed using the categorical-regression method (Gujarati 1995; Hardy 1993; Lawrence 1992; Sanford 1985). Since the repetition and geometry factors were classified into two different qualitative categories, dummy binary variables, which assume the values of either 0 or 1, e.g., 0 if the column is rectangular in shape and belongs to the "repeated shuttered" category, and 1 if circular and belongs to the "first shuttered" category, respectively, were introduced into the corresponding multiple regression models to quantify the average difference in labour productivity between the two categories; first and repeated shutter, as well as rectangular and circular geometry. The coding however is arbitrary and it would be just as valid to code rectangular-repeated shuttered columns with 1, and circular-first shuttered with 0.

Since regression models involve several independent variables having different units of measurement, a direct comparison of the size of various coefficients to assess their relative influence on the dependent variable, labour productivity, could be spurious. Therefore, before a meaningful investigation of the relative influence of the independent variables, i.e., buildability factors, can be conducted, the regression coefficients of the independent variables must be standardized (Jaccard and Turrisi 2003; Kim and Feree 1981; Lawrence 1992). The standardized 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 standardized using Eq. (6).

$$b_k{}^* = b_k \left(\frac{s_k}{s_y} \right), \tag{6}$$

where $b_k{}^*$ is the standardized 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, standardized regression coefficients are referred to as beta weights.

In addition, to determine the relative influence of such factors, the most influential factor was chosen to form 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 Eq. (7).

$$\frac{\textit{Standardized coefficient value of the } k^{th} \textit{ factor}}{\textit{Standardized coefficient value of the reference factor}}. \tag{7}$$

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, 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).

In addition, 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. Both coefficients determine how well the linear regression model is related to the data. 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 buildability factor's effect on labour productivity, i.e., positive or negative.

A. Macro-level Observation Analysis

A total of 182 labour productivity data points were collected at the macro level. The relationship between labour productivity and buildability factors was determined by the multiple categorical-regression model shown in Eq. (8).

$$\begin{aligned} P\,(\mathrm{m}^2/\mathrm{mh}) &= b_0 + b_1\,ALO + b_2\,VOC + b_3\,RF + \\ & b_4\,TSA + b_5\,ASA + b_6\,PCC. \end{aligned} \tag{8}$$

Where, as previously indicated, *ALO* is the ratio of total number of columns to total number of column axes as shown in Eq. (3); *VOC* is the total number of different column sizes, which represents the variability of column sizes; *RF* is a dummy variable indicating shutter repetition of columns observed, and quantifies the average difference in labour productivity between repeated and first shuttered columns; *TSA* is the total shutter area of columns (m^2), determined as shown in Eq. (1) (a&b); *ASA* is the average shutter area of columns (m^2), quantified as shown in Eq. (2); and *PCC* is the percentage of circular columns within the activity, determined as shown in Eq. (4).

The overall regression model and coefficients statistics are shown in Tables 1 and 2, respectively. The overall multiple categorical regression model quantifying the relationship between macro-level formwork labour productivity of columns and the relevant buildability factors was determined as shown in Eq. (9).

$$\begin{aligned} & P\,(\mathrm{m}^2/\mathrm{mh}) = 1.13 + 0.444\,ALO - 0.00360\,VOC - \\ & 0.167\,RF + 0.00146\,TSA + 0.157\,ASA - 0.0124\,PCC. \end{aligned} \tag{9}$$

Table 1 shows strong correlation and high determination coefficients between the investigated factors and labour productivity, i.e., 91.25% and 83.26%, respectively. Table 2 further shows that, apart from the variability of column sizes, all other investigated buildability factors are statistically significant in their effects on labour productivity, i.e., p-value < 0.050. In addition, the influence rank and relative influence values for the continuous factors are shown, with the percentage of circular columns and total shutter area being the most and least influential factors on formwork labour productivity, respectively.

Table 1. Overall regression model statistics for macro-level formwork labour productivity of columns

Correlation coefficient (*R*)	91.25%
Coefficient of determination (R^2)	83.26%
Standard error	0.317
F(6,175)	145.10
p-value	0.000
No. of observations	182

The regression coefficient value of the dummy variable shown in Table 2, quantifies the average difference in labour productivity between the two shutter repetition categories of columns, i.e., first and repeated. The sign and value quantified show that, on average, the difference in formwork labour productivity between first and repeated shutter of columns is –0.167 m^2/mh, i.e., labour productivity of first shuttered columns is less than repeated shuttered columns by 0.167 m^2/mh.

Table 2. Regression coefficients statistics for macro-level formwork labour productivity of columns

Coefficient	Value	p-value	Standardized coefficient value	Influence rank	Relative influence
ALO	0.444	0.000	0.260	3	0.60
VOC	–0.003 60	0.652	–0.0169	N/A	N/A
RF	–0.167	0.006 74	NA[1]	N/A	N/A
TSA (m^2)	0.001 46	0.000	0.193	4	0.44
ASA (m^2)	0.157	0.000	0.362	2	0.83
PCC	–0.0124	0.000	–0.434	1	1.00

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

The average percentage gain in labour productivity due to shutter repetition effect was determined by substituting the average values of buildability factors shown in Table 3 into Eq. (9), for the two categories of the dummy variables, 0 and 1, as follows:

Table 3. Average values of buildability factors influencing macro-level formwork labour productivity of columns

Buildability factor	Average value
ALO	1.48
VOC	6.55
TSA (m^2)	146.40
ASA (m^2)	5.50
PCC (%)	9.86

Therefore, the average percentage gain in formwork labour productivity of columns due to shutter repetition was quantified as follows:

First Shuttered Columns, RF = 1:

$$P(\mathrm{m}^2/\mathrm{mh}) = 1.13 + 0.444*(1.48) - 0.00360*(6.55) - 0.167*(1) + 0.00146*(146.40) + 0.157*(5.50) - 0.0124*(9.86) = 2.55.$$

Repeated Shuttered Columns, RF = 0:

$$P(\mathrm{m}^2/\mathrm{mh}) = 1.13 + 0.444*(1.48) - 0.00360*(6.55) - 0.167*(0) + 0.00146*(146.40) + 0.157*(5.50) - 0.0124*(9.86) = 2.72.$$

The average percentage gain in formwork labour productivity of columns due to shutter repetition was quantified as shown below:

$$\left[\frac{(2.72-2.55)}{2.55}\right] \times 100 = 6.67\%.$$

Approximately 7% increase in average formwork labour productivity is achieved due to shutter repetition in columns.

B. Micro-level observation analysis

At this level of observation, a total of 736 labour productivity data points were collected and distributed as follows:

a) Rectangular columns, 471 data points,
b) Circular columns, 265 data points.

The relationship between labour productivity and buildability factors at this level was determined by the multiple categorical-regression model shown in Eq. (10).

$$P(\mathrm{m}^2/\mathrm{mh}) = b_0 + b_1\,SA + b_2\,CGeom\,, \qquad (10)$$

where *SA* is the shutter area of the column (m^2); and *CGeom* is a dummy variable representing the geometry of the column observed, i.e., rectangular or circular, which quantifies the average difference in labour productivity between the two categories of columns. The value of 0 was selected to represent rectangular columns, whereas the value of 1 was used to denote circular columns.

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

Table 4. Overall regression model statistics for micro-level formwork labour productivity of columns

Correlation coefficient (*R*)	91.80%
Coefficient of determination (R^2)	84.27%
Standard error	0.453
F(2,733)	1964.38
p-value	0.000
No. of observations	736

Table 5. Regression coefficients statistics for micro-level formwork labour productivity of columns

Coefficient	Value	p-value	Standardized coefficient value	Influence rank	Relative influence
SA (m^2)	0.379	0.000	0.742	N/A	N/A
CGeom	–0.955	0.000	N/A	N/A	N/A

The relationship between formwork labour productivity of columns and the relevant buildability factors at the micro-level was therefore quantified by the following multiple categorical-regression model shown in Eq. (11).

$$P(\mathrm{m}^2/\mathrm{mh}) = 2.41 + 0.379\,SA - 0.955\,CGeom. \qquad (11)$$

To quantify the average percentage difference in micro-level formwork labour productivity between circular and rectangular columns, the average values of the corresponding buildability factors shown in Table 6, were substituted into Eq. (11) as follows:

Table 6. Average shutter areas of rectangular and circular observed columns

Column geometry	Total No. of observation	Average shutter area (m^2)
Rectangular	471	5.84
Circular	265	4.82
Total	736	5.47

Circular Columns, CGeom = 1:

$$P(\mathrm{m}^2/\mathrm{mh}) = 2.41 + 0.379 * (4.82) - 0.955 * (1) = 3.28\,.$$

Rectangular Columns, CGeom = 0:

$$P(\mathrm{m}^2/\mathrm{mh}) = 2.41 + 0.379 * (5.84) - 0.955 * (0) = 4.62\,.$$

The average percentage loss in labour productivity as a result of shuttering circular columns was determined as follows:

$$\left[\frac{(4.62 - 3.28)}{4.62}\right] \times 100 = 29.00\%\,.$$

In comparison with rectangular columns, an average loss of 29% in formwork labour productivity is associated with shuttering circular columns.

The regression coefficient value of the dummy variable shown in Table 5, quantifies the average difference in labour productivity between the two geometric categories of column shapes. The sign and value determined show an average loss of 0.955 m^2/mh in formwork labour productivity between shuttering circular and rectangular columns.

Consistent with the results obtained from the macro-level observation analysis, Table 4 shows strong correlation and high determination coefficients between the buildability factors and formwork labour productivity, i.e., 91.80% and 84.27%, respectively. Furthermore, Table 5 shows that the shutter area and shape geometry are significant in their effects on labour productivity, i.e., p-value < 0.050.

5. Discussion of Results

Apart from the variability of column sizes, the effects of the investigated buildability factors on formwork labour productivity of columns are significant. Although the researcher could not identify similar previous investigations with which to compare the findings of this study, the results obtained correlate well with the buildability principles on the one hand, i.e., design standardization, rationalization, and repetition, and the hypothesized effects of such factors by other researchers on construction productivity, on the other.

O'Connor *et al.* (1987) as well as Alshawi and Underwood (1993) discussed the negative effect of the variability of element sizes and the influence of grid patterns on the complexity of the construction process. However, their work was limited to general guidelines without any quantification of the impacts of such factors on the construction productivity. The results obtained by this study show that, although its impact is not statistically significant, the variability of column sizes within the activity does exhibit a negative influence on labour productivity. As the level of variability of sizes increases, additional contributory input is directed toward setting-out, reading plans, and identifying elements locations. Holding all other factors constant, for each additional column size introduced, an average loss of 0.0036 m^2/mh in labour productivity is realized. This pattern agrees with the concepts of design rationalization and standardization.

The importance of applying the concept of design standardization, on the one hand, and modularity (Goodrum *et al.* 2009), on the other, is also evident on the influence of grid patterns. In contrast to scattered and irregular positioning, uniform and symmetrical grid patterns facilitate setting-out maximum number of columns with minimum axes origins and measurements, therefore, accelerate the setting-out of the activity. This study has quantified a significant average gain of 0.444 m^2/mh in labour productivity as the column axes lay-out ratio increases by one unit. This finding further corroborates the positive effect of design standardization and modularity on the labour productivity of the operation.

Fischer and Tatum (1997) discussed the negative impact of circular columns on formwork productivity. Once again, their work comprised design guidelines and recommendations geared toward buildability knowledge and improvement; rationalizing and standardizing column geometry, as far as possible, yield a positive impact on formwork labour productivity.

The validity of this hypothesis is not only substantiated by this research, but also quantified. In comparison with rectangular shapes, forming circular columns is associated with added difficulties. Shuttering circular columns using traditional formwork material involves making round shapes strips, commonly 50 mm wide timber boards. Such strip-boards are assembled next to one another until the circle is complete. Pre-fabricated semi-circular moulds are placed face to face along each side of the semi-circumference at equal spacing which ranges from 500 mm to 1000 mm depending on the diameter of the column, to hold the timber strip-boards in position. Following this laborious task, each half of the column is transported to the required location and erected. This study quantified an average loss of 0.0124 m^2/mh in labour productivity as the percentage of circular columns observed at the macro-level increases by one unit. This pattern was also realized at the micro-level observation. On average, in comparison with rectangular sections, a loss of 29% in labour productivity is associated with shuttering circular columns.

Several previous research and literature discussed the importance and positive influence of repetition on productivity (CIRIA 1999; Dong 1996; Ferguson 1989; Fischer and Tatum 1997; Moore 1996; O'Connor *et al.* 1987). Labour inputs for formwork activities include substantial amount of laborious measurements, assembling, and at times, cutting to required sizes and shapes, which would be saved as a result of shutter size repetition. Furthermore, activity repetition makes the labour force progressively more familiar with the activity conditions and its sequence of operation. The findings of this study, quantitatively, confirmed such an importance. On average, an approximate gain of 7% in labour productivity as a result of formwork repetition of columns is achieved.

The importance of applying the rationalization concept to this activity is further substantiated by this investigation. The quantified effect and relative influence of the average size of columns indicates that the impact of shutter area is more dependent upon the average, which is dependent on the number of columns contained within the activity, than the total shutter area of all columns combined. The rationale underlying this finding may be explained by the following hypothetical discussion.

Column activities are composed of individual elements of different sizes, thus different shutter areas. The total shutter area recorded at the macro-level observation of this activity is the sum of the shutter areas of its individual constituents. If all, other influential variables, including the skill of operatives, are held constant, then, it may, theoretically, be assumed that column formwork labour productivity is approximately the same on two different construction sites having identical column formwork outputs, i.e., shutter area, but different number of columns. To further illustrate, if a construction site has, for instance, forty different small size columns, and another has twenty medium to large size columns, and if it is further assumed that the total formwork output of columns is the same on both sites, then it would be reasonable to expect similar labour productivity on both sites. However, if we consider the effect of design rationalization between the two sites, we may conclude higher labour productivity on the latter site; the related finding of this study substantiates the validity of such a conclusion. The quantified result shows that the effect of average formwork area is not only significant in its impact on labour productivity, but is also more influential than the total formwork area of columns.

The result of implementing the rationalization concept, although may yield larger elements in size, proved to be also positive in its effect on labour productivity. This study has quantified a significant relationship between labour productivity and the total area of formwork observed. Holding all other factors constant, a unit increase in formwork area is associated with 0.00146 m^2/mh and 0.379 m^2/mh increase in macro and micro-level average labour productivity, respectively.

This finding may be attributed to the following reasons: a) an initial contributory time is required by crew members to prepare work areas and formwork materials prior to commencing the direct or effective work. Therefore, if an activity is of a small-scale type, a major portion of the total input is directed toward contributory rather than effective work; b) the researcher observed during the data collection phase that it takes approximately the same input to erect, for instance, the shutter of a 400 mm × 400 mm column as for 500 mm × 500 mm; c) when crew members are confronted with large scale activities, better preparation, planning, and control is observed on sites; and d) in large scale monitored activities, crew members tend to work harder and take less frequent breaks.

In view of the preceding discussion, such an effect can be referred to as “economy of scale”, which is further augmented by the design rationalization concept.

6. 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 influence of buildability factors on the labour productivity of one of its major trades; formwork. Since columns formwork is among the labour intensive activities of reinforced concrete construction, and labour productivity is a fundamental piece of information for estimating and scheduling a construction project (Song and AbouRizk 2008), improving the labour efficiency of this activity would help reducing the risk of labour costs overrun and enhances the productivity of the operation.

The effects and relative influence of grid patterns; variability and repetition of column sizes; average and total areas of formwork erected; and the geometry of columns, on formwork labour productivity are determined and quantified. Apart from the variability of column sizes, which has further exhibited a negative impact on the efficiency of the forming operation, the investigated buildability factors, at both levels, macro and micro, are found to be significant in their impacts on labour productivity. In addition, the findings further corroborate the importance of applying the basic buildability principles, that is, design rationalization, standardization, and repetition of elements, to the design stage of construction projects.

Notwithstanding that general buildability 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 enhancement can be regarded as exhortations of good practice and common sense, often obtained using “Delphic Research Methods” (Cheetham and Lewis 2001). Conversely, the outcomes of this investigation provide practical guidelines for buildability effects based upon quantified results obtained through rigorous research and analysis; thus can be useful for “formalizing” the specific buildability knowledge of this activity, on the one hand, and helpful to industry researchers and practitioners in evaluating productivity performances in a much more effective way, on the other (Lin and Huang 2010).

The findings fill a gap in buildability knowledge of factors impacting columns formwork operatiowhich can be used to provide designers feedback on how well their designs consider the requirements of buildability principles, and the consequences of their decisions on labour efficiency. Moreover, the depicted patterns of results may provide guidance to construction managers for effective activity planning, scheduling, resource levelling, and efficient labour utilization.

Although several findings have been drawn from this study, further research into the effects of buildability factors on formwork productivity, which are common to other structural elements of in situ reinforced concrete construction such as, foundations, walls, beams, and slabs, is recommended.

Due to the modicum differences in column heights observed, the exploration of the height effect on formwork labour productivity could not be determined. Therefore, the impact of this factor should be further investigated and quantified. On the other hand, since this research focused on the traditional formwork type, it is further recommended to explore the influence of other types such as, glass fiber reinforced plastic (GRP), steel, and aluminium, on columns formwork labour productivity.

The findings of this research, in addition to other structural elements recommended for exploration, can be ultimately used to develop an automated "Buildability Design Support System". Such a system would be useful for formalizing the specific buildability knowledge of formwork trade to make it readily available to designers, hence improving the performance of projects in an ever-increasing demand for faster and lower cost delivery of constructed facilities.

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STATYBOS VEIKSNIŲ ĮTAKA DARBO NAŠUMUI ĮRENGIANT KOLONŲ KLOJINIUS

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Santrauka

Statybos veiksnių įtaka gelžbetoninių konstrukcijų, kaip antai pamatų, sienų, kolonų, sijų ir perdangos plokščių, klojinių, įrengimo darbo našumui turi būti nustatyta ir kiekybiškai įvertinta. Vienetinės darbo sąnaudos kolonos klojiniams įrengti, palyginti su kitomis gelžbetoninio rėmo dalimis, yra didesnės, nes sudėtinga suformuoti elementus, ypač kai kolonos yra ne stačiakampio formos. Todėl šio tyrimo tikslas – nustatyti statybos veiksnių įtaką kolonų klojinių įrengimui. Siekiant šio tikslo buvo surinkta daug duomenų apie darbo našumą ir šie duomenys buvo ištirti naudojant kategorijų-regresijos metodą. Buvo įvertinti šie veiksniai: ašių tinklas, kolonų dydžio įvairovė, kartojimasis, bendrasis ir vidutinis užrakto dydis, geometrija. Neįvertinus kolonų dydžio įvairovės, gauti rezultatai rodo didžiulį šių veiksnių poveikį darbo našumui. Naudojantis šia informacija galima įvertinti, ar projektuotojas atsižvelgė į statybos principus ir priimtų sprendimų įtaką darbo našumui. Be to, rezultatai gal suteikti papildomos informacijos darbų vadovui, kaip efektyviau panaudoti darbo jėgą.

Reikšminiai žodžiai: statybos veiksniai, kategorinė regresija, kolonos, klojiniai, darbo našumas, racionalizavimas, kartojimas, standartizacija.

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