

# The effects of buildability factors on formwork labor productivity of grade beams

## Efectos de los factores de edificabilidad sobre la productividad laboral de moldajes de vigas en fundaciones

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### Abstract

Buildability is one of the most important factors affecting labor productivity. Nonetheless, an extensive search of the literature revealed a dearth of research into its effects on in situ reinforced concrete construction, especially at the formwork trade level. Despite the importance of this trade to in situ reinforced concrete material, the influence of buildability factors on formwork labor productivity of major structural elements are yet to be quantified in measurable terms. Grade beams are important structural elements which are primarily used to provide one, or a combination, of the following functions: (1) tie the building foundations to provide the required lateral stiffness at the sub-structural levels; (2) reduce the unsupported free length of columns below grade level; and (3) limit excessive differential settlements of isolated foundations. Therefore, the objective of this research is to investigate and quantify the effects and relative influence of the following buildability factors on formwork labor efficiency of this activity: (a) variability of beam sizes; (b) beam sizes; and (c) number of joints formed at beams intersections. To achieve this objective, a large volume of productivity data was collected and analyzed using the multiple regression method. As a result, the effects and relative influence of the buildability factors investigated are determined. Apart from the variability of beam sizes, the findings show significant effects of these factors on formwork labor 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 labor efficiency. On the other hand, the depicted patterns may provide guidance to construction managers for effective activity planning and efficient labor utilization.

Keywords: Concreto, morfología de agregados, análisis de imágenes, resistencia a la compresión, trabajabilidad

### Resumen

La edificabilidad es uno de los factores principales que afecta la productividad laboral. Sin embargo, una extensa revisión de la literatura reveló la ausencia de investigación sobre sus efectos en obras de construcción de concreto reforzado, especialmente a nivel del oficio del trabajo de moldeado. A pesar de la importancia de este oficio para el concreto reforzado en obras, la influencia de los factores de edificabilidad sobre la productividad del oficio del moldeado sobre elementos estructurales mayores, aún está por ser cuantificada en términos medibles. Las vigas en fundaciones son elementos estructurales importantes, usados para proporcionar una, o una combinación de las siguientes funciones: (1) amarrar los cimientos de la edificación y proporcionar la rigidez lateral en los niveles sub-estructurales; (2) reducir la longitud libre de las columnas sin soporte, bajo el nivel de la rasante; (3) limitar el excesivo diferencial de asentamientos en los cimientos aislados. Por lo tanto, el objetivo de esta investigación es analizar y cuantificar los efectos e influencia relativa de los siguientes factores de edificabilidad, sobre la eficiencia del trabajo de moldeado de esta actividad: (a) la variabilidad del tamaño de las vigas, (b) tamaño de las vigas, (c) cantidad de juntas resultantes de las intersecciones de las vigas. Con el fin de lograr este objetivo, un gran volumen de datos sobre la productividad ha sido recopilado usando un método de regresión múltiple. Como resultado, se determinaron los efectos e influencia relativa de los factores de edificabilidad investigados. A parte de la variabilidad de tamaño de las vigas, los descubrimientos indican significativos efectos de estos factores sobre la productividad del trabajo de moldeado, la que puede ser empleada para entregar un comentario a los diseñadores sobre cuán bien sus diseños consideran las necesidades de los principios de edificabilidad, y las consecuencias de sus decisiones sobre la eficiencia laboral. Por otro lado, los patrones descritos pueden servir como guía a los administradores de la construcción para una efectiva planificación de actividades y utilización laboral eficiente.

Palabras Clave: Edificabilidad, constructabilidad, moldeado, vigas rasantes, productividad laboral

## 1. Introduction

Construction is the world's largest and most challenging industry (Tucker, 1986). In 1997,

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the US construction industry accounted for 10% of Gross Domestic Product (GDP) and employed over 10 Million, making the industry the largest in the country (Allmon et al., 2000). On the other hand, Horner et al. (1989) indicated that a 10% increase in construction labor productivity would yield annual savings of about £1 Billion to the British economy; a similar conclusion was echoed by Stoekel and Quirke (1992).

Several factors affect labor productivity, but buildability is among the most important (Adams, 1989; 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: (a) rationalization; (b) standardization; and (c) repetition of elements (Dong, 1996). Design rationalization is defined as “the minimization of the number of materials, sizes, components or sub-assemblies”, 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, 1996b). The design repetition principle involves repeating bay layout, floor grids, dimensions of elements, and storey height.

The influence of buildability on the construction process has been the subject of numerous previous investigations (Lam and Wong, 2009; Saghatforoush et al., 2009; Lam et al., 2007; Trigunaryah, 2007, 2004; Pulaski and Horman, 2005; Poh and Chen, 1998; Fischer and Tatum, 1997; Hyde, 1996; Moore, 1996a; Moore, 1996b; Alshawi and Underwood, 1996; Griffith, 1987; O'Connor et al., 1987) to name a few. However, a thorough examination of the literature revealed a dearth of research into the influence of buildability on the labor productivity of an integral trade of the in situ reinforced concrete material; namely, formwork. Furthermore, most of the previous buildability studies were heuristic in principles, generic and qualitative in nature; few were even rudimentary, based upon anecdotal perceptions, insights and common sense.



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 labors comprises approximately thirty percent (McTague and Jergeas, 2002). Nevertheless, the influence of buildability on this trade, especially at the activity levels, is yet to be determined and quantified.

Grade beams are one of the important elements of in situ reinforced concrete construction. Primarily, such elements are used to serve one, or a combination, of the following structural functions: (1) tie building foundations to provide the required lateral stiffness at the sub-structural levels; (2) reduce the unsupported free length of columns, below grade level, to minimize the effect of buckling; and (3) limit excessive differential settlements of isolated foundations. In addition, grade beams may be used to provide support to masonry walls. Formwork of grade beams is a labor intensive operation, which is associated with added difficulty due to performing the activity below the grade level. Therefore, the objective of this research is to investigate the effects and relative influence of the following buildability factors on their formwork labor productivity: (a) variability of beam sizes; (b) size of beams; and (c) number of joints formed as a result of beams intersections. Consequently, labor productivity, thus labor cost and benefits related to the application of buildability principles, can be estimated for the various levels both, reliably and with reasonable accuracy.

To develop an understanding of the previous research that had been conducted and the progress developed in the area of buildability, 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 a recommendation geared towards encouraging further investigations into the effects of buildability on other elements and trades of in situ reinforced concrete structures.

## 2. Literature review

The US Department of Commerce defines productivity as “Dollars of output per person-hour of labor input” (Adrian, 1987). Handa and Abdalla (1998) defined productivity as “the ratio of outputs of goods and/or services to inputs of basic resources, e.g., labor, 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”.

In view of the preceding discussion, it is obvious that the general consensus to define productivity is the ratio of output to input. Thus, 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).

The advantages of the single factor productivity, e.g., labor 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 labor productivity measure the popular option, especially for researchers, since effective control systems monitor each input separately. In addition, since construction is a labor intensive industry, it may be argued that man-power is the only productive resource, thus construction productivity is mainly dependent upon human effort and performance.

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 a new form of relationship between designers and constructors was suggested. 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).

Based on this definition, two implications may be inferred. First, buildability can be categorized in a scale ranging from good to bad; and second, each building has overall requirements which may conflict with the buildability concept, thus necessitate the acceptance of less than good buildability.

Throughout Europe, the expression "Buildability" is the adopted terminology for the influence of design on the construction process. On the other hand, the term "Constructability" is widely used and favored in North America. The constructability task force of the Construction Industry Institute (CII) defines constructability as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (CII, 1986). Although both expressions target similar issues, the term constructability covers wider range of disciplines including conceptual planning, design, procurement and construction.

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 (RICS) was a comparison between construction operations of the UK and the US, with emphasis on design and contractual procedures. They concluded that “design cannot be divorced from construction without major time and cost penalties” (RICS, 1979). 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 the achievement of good buildability was provided.

In an effort to facilitate the implementation of the constructability concept in the construction industry, the Construction Industry Institute (CII, 1993) has developed 17 constructability concepts, which are grouped under the three main phases of the construction project: (a) conceptual planning; (b) design and procurement; and (c) field operations. While such an effort is most certainly a step in the right direction, the benefits of applying the related concepts to each phase of the project’s life cycle are yet to be determined in tangible terms.

O'Connor et al. (1987) and Alshawi and Underwood (1996) discussed the negative effect of the variability of element sizes 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 construction productivity. 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, e.g., width, length, depth, and type. Yet, the effects of such variables on construction productivity were not measured.

In an effort to measure the buildability of designs, the “Buildable Design Appraisal System” (BDAS), was established by the Construction Industry Development Board of Singapore (CIDB, 1995). The primary objective of the BDAS is to assess the influence of design on construction productivity.



The BDAS presents a systematic numerical method to appraise the effects of design on site efficiency and productivity by means of calculating the “Buildable Score” of the design taking into consideration the level of simplicity, standardization, and the extent of the single integrated elements, i.e., combining related components into a single element. Indices are awarded for each type of architectural and structural systems based on the level of difficulty of the construction operation. Designs with high buildable scores suggest more efficient use of labor, hence higher labor productivity.

A major shortcoming of this appraisal system however stems from the lack of depth in which buildability was assessed. Buildable scores are awarded based on the overall structural type and construction method. Such an approach is too general in nature where the impacts of buildability factors require investigations in far greater depth to establish and quantify their effects on labor productivity.

Although the BDAS is the only available quantitative design appraisal tool to date, the scientific reliability of the methodology employed in developing the system's buildable scores is questioned. Buildable scores were obtained from inputs provided by government agencies, private consultants, and product manufacturers based upon previous personal and group experience and judgment (Dong, 1996). While such an approach can be regarded as good practice and common sense, the scientific method requires facts to be established and supported by rigorous research, measurement, and analysis. Moreover, Poh and Chen (1998), in an empirical study of 37 completed buildings, determined inconsistent patterns among buildable scores, labor productivity, and construction cost, thus went on to conclude that “while a design with a high buildable score will result in more efficient labor usage, the relationship between the buildable score and construction cost is less distinct”.

In advocating for the implementation of buildability principles, CIRIA (1999) on the other hand, stated that the application of the rationalization and standardization concepts provides site efficiency, predictability, and better value for money. However, no direction was suggested on how to assess or quantify such benefits in tangible terms.

Even though seminal work has been developed, apart from the BDAS, in none of the mentioned examples, were there any quantified or quoted figures, or even a suggestion on how to assess the buildability impact on construction activities. In addition, previous research has not provided “specific” guidance on how to measure the buildability of a design. In one of the few text books entirely devoted to buildability, Ferguson (1989) shows the breadth of factors which must be considered to make a design buildable and provides many examples of buildability problems and suggestions for improvements. While such suggestions allow the classification of buildability issues according to their level of details, they do not link buildability issues to “specific” design decisions.

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

Formwork types are grouped according to their application as follows (Ricouard, 1982): (1) vertical formwork, where the concrete lateral pressure is the governing factor. Examples of this type involve columns and walls; and (2) 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, aluminum, 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 preceding discussion, it may be concluded that each type of the previously presented materials is associated with its own task-level difficulty, hence can also be an influential buildability factor on the labor productivity of the formwork operation. However, Since Grade Beams are elements which are neither subject to repetition within the construction site, nor require high finishing quality, in all sites monitored, the “traditional” formwork, was the type used for this activity.

Grade beams formwork observed comprised plywood vertical sheets supported by timber vertical studs, which are supported by timber stringers at both, top and bottom parts, and tied around mid depth by a “leave-in” metal tie. If the depth of the grade beam is larger than 1000 mm, usually a middle stringer is added to enhance the stiffness of the forms. The stringers are supported by diagonal braces along the span of the beam. Diagonal braces are further supported by timber boards, which are securely nailed into the concrete blinding underneath the beam.

The major tasks of grade beams formwork operation on sites include: (a) setting-out; (b) leveling, identifying locations of the different beam sizes, measuring, and locating beams intersections; (c) cutting, placing, and securing sides in positions; and (d) plumbing, tying, and bracing sides in place.

Based on the previous discussion, it can be hypothesized that the following buildability factors impact the task level difficulty of grade beams formwork, thus the labor productivity of the operation: (1) variability of beam sizes; (2) size of beams; and (3) number of joints formed due to beams intersections within the overall activity, and along the single beam formed.

#### 4. Research method and analysis

The labor productivity data of this activity were collected at both levels; macro, and micro. Macro-level observation involved monitoring the overall activity within the project, i.e., forming all ground beams shown on the relevant drawings, where the total productive labor inputs associated with completing the overall activity was recorded, therefore, a single labor productivity index was achieved, that is, the total area of formwork erected for all ground beams per total productive man-hours used to complete the activity. The labor 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 the different beam size locations, measuring, and cutting, as well as “direct” or “effective” forming time used in sides assembling, placing in positions, securing,

plumbing, tying, and bracing in place (Jarkas, 2005; Chan and Kumaraswamy, 1995; Salim and Bernold, 1994). 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 the “direct” or “effective” productive forming labor inputs were used to quantify the labor productivity of beams observed (Jarkas, 2005).

The advantages of monitoring an activity at the micro-level are twofold: (1) the results obtained would assist in cross-referencing patterns obtained from the macro-level observation analysis, which can further provide 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., communication complexity, sequencing problems, site lay-out, and proportion of work subcontracted, on labor productivity are minimized at this level of observation.

Since numerous factors, other than buildability, influence labor productivity on sites, which may mask or even overshadow the effect of buildability on the forming operation, the focus was on selecting construction projects which shared common features such as, contract procurement method, geographical locations, and to a large extent, construction methods, yet differed in types and magnitudes, so that the impacts of the explored buildability factors could be unraveled; similar sites, largely share similar characteristics of buildability factors, especially at the activity level, thus their influence may not be best revealed.

On the other hand, the differences in management procedures applied among the various types and magnitudes of sites monitored, at the project level, have little effect at the activity level of observation, whereas, the possible impacts of other interfering factors such as, crew size and composition, skill of labors, motivation, and supervision quality can be moderated by collecting a large volume of labor productivity data (Jarkas, 2005). Consequently, sites observed included residential and office buildings, commercial centers,

and industrial facilities, which ranged from US\$ Million 0.80 to 3.50 in construction cost, 1 to 8 floors in height, and 300 m<sup>2</sup> to 4000 m<sup>2</sup> in “foot-print” areas.

In an effort to minimize the negative influence of interruptions and disruptions on labor productivity, major encountered delays during the forming process, e.g., material shortage, unavailability of tools, accidents, and inclement weather, were recorded and discounted, where only productive labor inputs were used to quantify the labor productivity indices.

The formwork labor productivity data of this activity, which were part of a larger research project, were collected from thirty different construction sites located in the State of Kuwait, where in situ reinforced concrete material is the prevailing type of construction. In addition to the main projects selected for observation, relevant data were further collected from several other sites to supplement the volume of productivity data. The data collection duration spanned a period of nineteen months, in which, a total of 54 and 334 labor productivity data points, i.e., indices, were determined 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-level labor inputs for the corresponding grade beams observed were collected using the intermittent and direct observation techniques, respectively (Jarkas, 2005; Williamson, 1999; 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 labor inputs, and to record the major delays encountered in the forming operation. The intermittent observation technique involved collecting macro-level labor inputs upon the completion of the activity, yet conducting occasional site visits during the process 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 were usually completed within the same day, or during the progress of the activity. Therefore, micro-level labor inputs were collected on daily basis.

The data collected at the macro-level were cross-checked by both; superintendents and foremen, whereas micro-level data were double-checked by different crew members, who were also involved in the forming operation of selected beams, for verification and accuracy. In addition, beams monitored were visually inspected and marked on related drawings for output measurements.

The buildability factors explored, which are common to grade beams formwork activity, as previously stated, included: (1) the variability of beam sizes; (2) beam sizes; and (3) the number of joints formed as a result of beams intersections. Commonly, grade beams vary in sizes within the activity in accordance with spans and resisting loads. Therefore, the size variability factor was represented by the total number of the different sizes encountered within the project observed, whereas the beam size factor was determined by the physical erected formwork area of beams.

The total formwork output of grade beams is the total sum of all formwork areas of single beams contained within the activity. Since grade beams are fixed directly on grade, only beam sides were used to quantify the formwork outputs. The “shutter” area of a single grade beam was therefore quantified as shown in Equation 1.

$$[\text{Profundidad de la viga/Depth of beam side (m)} * 2] * \text{Luz de la viga/Total span of beam (m)} \quad (1)$$

The intersection of beams factor was denoted by the total number of joints formed along the span as depicted in Figure 1.

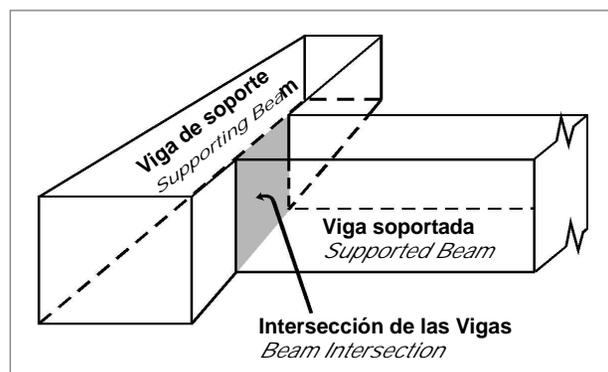


Figura 1. Moldeado de junta de intersección de dos vigas  
Figure 1. Formwork joint at the intersection of two beams

As previously indicated, 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 and distributing forms within the jobsite, reading plans, identifying beam locations, measuring, and cutting, are of little influence on the productivity of the operation at this level of observation. In view of this, buildability factors explored at the micro level were limited to the size of the grade beams observed, and the number of joints formed along beams monitored due to intersections.

The labor inputs collected at the macro and micro-levels were screened for possible measurement errors or outliers, i.e., an unusual observation which lies outside the range of the data values. On the other hand, the outputs of buildability factors explored were determined by the researcher using the “physical unit of measurement” technique (Talhouni, 1990). The labor productivity indices for beams observed were then quantified as shown in Equation 2.

$$Productividad\ Laboral / Labor\ productivity\ (m^2/mh) = \frac{\text{Área de moldeado emplazada} / \text{Area of formwork erected} (m^2)}{\text{Insumo de trabajo} / \text{Labor input} (mh)} \quad (2)$$

The descriptive statistics of the labor productivity determined and buildability factors investigated, at both levels, macro and micro, are provided in Tables 1 and 2, respectively.

Tabla 1. Estadísticas Descriptivas a Nivel Macro de Factores de Edificabilidad y Productividad Laboral para el del Moldeado de vigas rasantes  
 Table 1. Macro-Level Descriptive Statistics of Buildability Factors and Formwork Labor Productivity of Grade Beams

Factor de Edificabilidad/Buildability Factor	Valor Mínimo/ Minimum Value	Valor Máximo/ Maximum Value	Valor Promedio/ Average Value	Desviación Estándar/ Standard Deviation
Variabilidad de las Vigas/Variability of Beams (VOB)	1.00	4.00	1.59	0.74
Área Total de Postigo/Total Shutter Area (TSA (m <sup>2</sup> ))	11.72	802.00	203.57	175.58
Número total de juntas resultantes/Total Number of Joints Formed (TNOJ)	0.00	51.00	14.78	15.84
Productividad Laboral del Moldeado/Formwork Labor Productivity (m <sup>2</sup> /mh <sup>1</sup> )	Valor Mínimo/ Minimum Value	Valor Máximo/ Maximum Value	Valor Promedio/ Average Value	Desviación Estándar/ Standard Deviation
	2.44	8.10	4.28	1.18

<sup>1</sup> mh indica horas-hombre  
<sup>1</sup> mh denotes man-hour



Tabla 2. Estadísticas Descriptivas a Nivel Micro de Factores de Edificabilidad y Productividad Laboral para el del Moldeado de vigas rasantes

Table 2. Micro-Level Descriptive Statistics of Buildability Factors and Formwork Labor Productivity of Grade Beams

Factor de Edificabilidad/Buildability Factor	Valor Mínimo/ Minimum Value	Valor Máximo/ Maximum Value	Valor Promedio/ Average Value	Desviación Estándar/ Standard Deviation
Área de Postigo/Shutter Area (SA (m <sup>2</sup> ))	0.80	61.32	10.31	10.91
Número de juntas/Number of Joints (NOJ)	0.00	6.00	0.81	1.19
Productividad Laboral del Moldeado/Formwork Labor Productivity (m <sup>2</sup> /mh)	Valor Mínimo/ Minimum Value	Valor Máximo/ Maximum Value	Valor Promedio/ Average Value	Desviación Estándar/ Standard Deviation
	1.37	19.36	6.90	2.94

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, i.e., graphical techniques for normality assessment, where the ordered response values or observations are plotted as a function of the corresponding normal order statistic means, commonly referred to as the “Z” value, of labor productivity data revealed that the values belong to almost normally distributed populations, thus validating the statistical reliability inferences (Sincich et al., 2002). A sample plot of the micro-level formwork labor productivity of beams observed is shown in Figure 2.

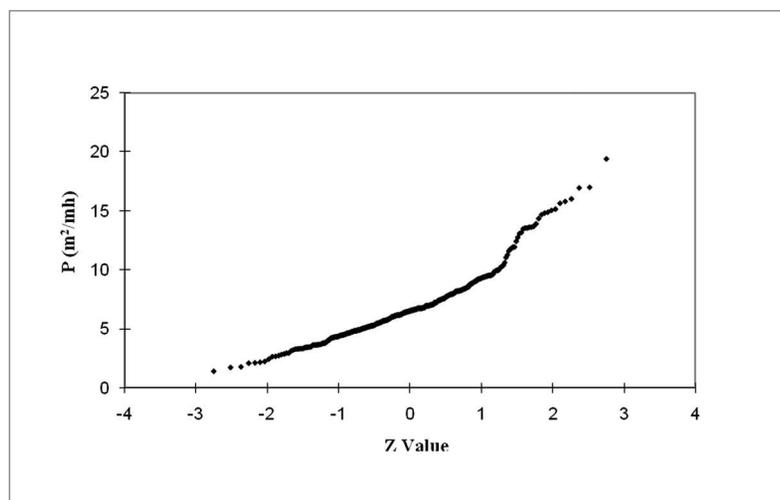


Figure 2. Micro-level labor productivity normal probability plot of ground beams observed  
Figura 2. Gráfico de probabilidad normal de la productividad laboral, a nivel micro, de las vigas a piso observadas

The effects and relative influence of buildability factors on labor productivity were analyzed using the multiple regression method (Gujarati, 1995; Lawrence, 1992; Sanford, 1985; Sincich et al., 2002). It is important to note that since the 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, i.e., labor 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). The standardized regression coefficients are then measured on the same scale, with a mean of "0" and a standard deviation of "1", 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 the following formula:

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

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 by the following formula:

$$\frac{\text{Influencia relativa del factor } k^{th}}{\text{Relative influence of the } k^{th} \text{ factor}} = \frac{\text{Valor coeficiente estandarizado del factor } k^{th} / \text{Standardized coefficient value of the } k^{th} \text{ factor}}{\text{Valor coeficiente estandarizado del factor de referencia / Standardized coefficient value of the reference factor}} \quad (4)$$



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

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

#### a) Macro-level observation analysis

A total of 54 labor productivity indices were quantified at the macro level. The relationship between labor productivity and buildability factors was determined by the multiple regression model shown in Equation 5.

$$P (m^2/mh) = b_0 + b_1 VOB + b_2 TSA + b_3 TNJ \quad (5)$$

Where, *VOB* represents the number of the different sizes of grade beams observed within the activity; *TSA* ( $m^2$ ) is the total formwork area of grade beams observed, determined as shown in Equation 1; and *TNJ* denotes the total number of joints formed in grade beams as a result of intersections, as depicted in Figure 1.

The overall regression model and coefficients statistics are shown in Tables 3 and 4, respectively.

Tabla 3. Modelo Estadístico de Regresión General para Productividad Laboral, a nivel macro, del moldeado de vigas rasantes  
 Table 3. Overall Regression Model Statistics for Macro-Level Formwork Labor Productivity

Correlation Coefficient (R)/Coeficiente de correlación (R)	93.90%
Coefficient of Determination (R <sup>2</sup> )/Coeficiente de determinación (R <sup>2</sup> )	88.20%
Standard Error/Error estándar	0.418
p-value	0.000
No. of Observations/No. de observaciones	54

Tabla 4. Coeficientes de Regresión Estadísticos para la Productividad Laboral, a nivel macro, del Moldeado de vigas rasantes  
 Table 4. Regression Coefficients Statistics for Macro-Level Formwork Labor Productivity of Grade Beams

Coefficient Coeficiente	Value Valor	Standard Error Error Estándar	p-value Valor-p	VIF <sup>1</sup>	Standardized Coefficient Value Valor Coeficiente Estandarizado	Influence Rank Rango de Influencia	Relative Influence Influencia Relativa
VOB	-0.00297	0.0815	0.971	1.10	-0.00186	N/A <sup>2</sup>	N/A
TSA (m <sup>2</sup> )	0.00720	0.000405	0.000	1.53	1.07	1	1.00
TNJ	-0.0203	0.00466	0.000	1.66	-0.273	2	0.26

<sup>1</sup> El factor de variación de inflación determina el nivel de correlación, entre los factores independientes de edificabilidad en el modelo. Un valor VIF mayor que 10 indica una multicolinealidad severa, determinando así los resultados estadísticos.

<sup>1</sup> Variance inflation factor determines the level of correlation among the independent buildability factors in the model. A VIF value greater than 10 indicates severe multicollinearity, thus undermining the statistical results.

<sup>2</sup> El rango de influencia y la influencia relativa solo de factores de edificabilidad estadísticamente importantes, es decir, valor-p < 0.050, fue determinado para productividad laboral.

<sup>2</sup> The influence rank and relative influence of only statistically significant buildability factors, i.e., p-value < 0.050, on labor productivity were determined.

The relationship between formwork labor productivity and the relevant buildability factors at the macro-level was therefore quantified as shown in Equation 6.

$$P (m^2/mh) = 3.12 - 0.00297 VOB + 0.00720 TSA - 0.0203 TNJ \quad (6)$$

Table 3 shows strong correlation and high determination coefficients between the explored factors and labor productivity, i.e., 93.90% and 88.20%, respectively. Table 4 further shows that, apart from the variability of grade beam sizes, the size and total number of joints formed due to intersections of these elements, are statistically significant in their effects on labor productivity, i.e.,  $p$ -value  $< 0.050$ . In addition, the influence rank and relative influence values are shown, with the size factor being more influential than the number of joints formed, on labor productivity.

b). Micro-level observation analysis

At this level of observation, a total of 334 labor productivity indices were determined. The relationship between labor productivity and buildability factors was determined by the multiple regression model shown in Equation 7.

$$P (m^2/mh) = b_0 + b_1 SA + b_2 NJ \quad (7)$$

Where,  $SA (m^2)$  represents the formwork area of the observed beam; and  $NJ$  expresses the number of joints formed.

The overall regression model and coefficients statistics are shown in Tables 5 and 6, respectively.

Tabla 5. Modelo estadístico de regresión general para productividad laboral del moldeado de vigas rasantes, a nivel micro  
Table 5. Overall regression model statistics for micro-level formwork labor productivity of grade beams

Correlation Coefficient (R)/Coeficiente de correlación (R)	90.22%
Coefficient of Determination (R <sup>2</sup> )/Coeficiente de determinación (R <sup>2</sup> )	81.40%
Standard Error/Error estándar	1.27
p-value	0.000
No. of Observations/No. de observaciones	334

Tabla 6. Coeficientes de regresión estadísticos para la productividad laboral del moldeado de vigas rasantes, a nivel micro.  
Table 6. Regression coefficients statistics for micro-level formwork labor productivity of grade beams

Coefficient Coeficiente	Value Valor	Standard Error Error Estándar	p-value Valor-p	VIF	Standardized Coefficient Value Valor Coeficiente Estandarizado	Influence Rank Rango de Influencia	Relative Influence Influencia Relativa
SA (m <sup>2</sup> )	0.244	0.00642	0.000	1.01	0.908	1	1.00
NJ	-0.242	0.0586	0.000		-0.0987	2	0.11

The relationship between micro-level formwork labor productivity of grade beams and the relevant buildability factors was quantified by the multiple regression model shown in Equation 8.

$$P (m^2/mh) = 4.58 + 0.244 SA - 0.242 NJ \quad (8)$$

Consistent with the results obtained from the macro-level observation analysis, Table 5 shows strong correlation and high determination coefficients between the buildability factors and formwork labor productivity, i.e., 90.22% and 81.40%, respectively. Furthermore, Table 6 shows that both factors remain statistically significant in their effects, i.e., p-value < 0.050, with the size factor being more influential in its impact than the number of joints formed on labor productivity.

## 5. Discussion of results

Apart from the variability of grade beam sizes, the effects of the investigated buildability factors on formwork labor productivity are significant. Although the author could not identify previous quantitative research, with which to compare the findings of this investigation, the results obtained correlate with the buildability concept on the one hand, and fall within the design rationalization and standardization principles advocated for in previous studies (CIRIA, 1999; Fischer and Tatum, 1997; Dong, 1996), on the other.

O'Connor et al. (1987) and Alshawi and Underwood (1996) discussed the negative effect of the variability of element sizes on the complexity of the construction process. Nevertheless, their work was limited to general guidelines without any quantification of the influence of such factors on construction productivity. The results obtained by this investigation show that, although its impact is not statistically significant, the variability of grade beam sizes within the activity does exhibit a negative effect on formwork labor productivity. As the level of variability of sizes increases, additional contributory input is directed towards setting-out, reading plans, and identifying the locations of the different beam sizes. Holding all other factors constant, for each additional grade beam size introduced, an average loss of 0.00297 m<sup>2</sup>/mh in labor productivity is realized. This pattern agrees with the design rationalization and standardization principles.

The result of implementing the rationalization principle, although may yield larger elements in size, proved to be also positive in its effect on labor productivity. This study has quantified a significant relationship between labor productivity and the total area of formwork observed. Holding all other factors constant, a unit increase in formwork area is associated with 0.00720 m<sup>2</sup>/mh, and 0.244 m<sup>2</sup>/mh increase in macro, and micro-level labor 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, for an approximately equal beam span, it takes approximately the same labor input, for instance, to form a 300 x 600 mm grade beam as for 400 x 700 mm in cross section; (c) when crew members are confronted with large scale activities, better preparation, planning and control was further 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 may be referred to as “economy of scale”.



The negative impact of intersections on formwork labor productivity of grade beams further corroborates the importance of applying the rationalization and standardization principles to the design stage of this activity. Intersection of grade beams occurs when a beam frames onto another beam. This situation is frequent, not only in grade beams, but also in suspended beams. When encountered, a joint or opening having the same dimension of the supported beam is formed in the supporting beam at the location of the intersection. When a beam is supporting one or several beams, especially if the supporting and supported grade beams differ in depth, additional labor input is required for measurement, cutting, and fixing supporting beam sides. Therefore, applying the rationalization and standardization principles to this activity, results in a substantial saving in labor input, thus enhancing the efficiency of the forming operation. The results obtained indicate that; holding all other factors in the regression models constant, on average, an incurred loss of 0.0203 m<sup>2</sup>/mh, and 0.242 m<sup>2</sup>/mh in macro and micro-level labor productivity, respectively, is associated with each unit increase in the number of joints formed as a result of such intersections.

## 6. Conclusions and a recommendation 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 labor productivity of one of its labor intensive major trades; formwork. Since grade beams are among the major activities which are frequently encountered on many construction sites, improving its labor productivity can help reducing the risk of labor costs overrun and increases the efficiency of the operation.

This research has quantified the effects and relative influence of the variability of grade beam sizes, beam sizes, and number of beams intersections on formwork labor productivity. Apart from the variability of sizes, which also exhibits 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 effects on labor productivity.



The results obtained, not only corroborate the importance of applying the “rationalization” and “standardization” principles, in particular, “modularity”, to the design stage of construction projects, through facilitating the process of learning, thus enables the operatives to predict problems and stream-line the problem-solving process, avoid errors, share information, and reduce waste materials, therefore, enhances their efficiency and optimizes the expenditure of the building evolution, but also substantiate the positive impact of the “economy of scale” concept, which is further augmented by the application of these principles, on the productivity of the forming operation. Furthermore, it can be argued that such a positive contribution improve the quality of construction, which is, in comparison with other industries, poor due to low skilled-high turnover operatives.

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

The outcomes of this investigation fill a gap in buildability knowledge and measurement of factors impacting grade beams formwork operation, which can be used to provide designers feedback on how well their designs consider the requirements of the buildability principles, and the consequences of their decisions on labor productivity. On the other hand, the depicted patterns of results may provide guidance to construction managers for effective activity planning and efficient labor utilization.

Although several findings have been drawn from this study, further research into the effects of buildability factors on formwork, and other related trades of in situ reinforced concrete material, i.e., rebar fixing and concreting, labor productivity, which are common to other structural elements of in situ reinforced concrete construction such as, foundations, walls, columns, beams, and slabs, is recommended. The findings of this investigation, in addition to other trades and structural elements recommended for exploration, can ultimately be used to develop an automated "Buildability Design Support System". Such a system would be useful for formalizing the specific buildability knowledge of reinforced concrete construction, hence improving the performance of projects in an ever-increasing demand for faster and lower cost delivery of constructed facilities.

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