Establishing the Effect of Building Design on Construction Work

by

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ABSTRACT

Design is widely accepted as a factor that affects construction work. Although knowledge about this effect will contribute to the improvement of construction practice, this is very limited. No study has been focused on establishing how the effect of design on construction work can be evaluated.

The primary objective of this research was to formulate an approach enabling the assessment of the effect of building design on construction work. To achieve this, a quantitative index based on field data, termed the 'index of difficulty,' was established. Given a construction activity, this index relates the effective work effort per unit of output expended in completing a construction part under two distinct designs: one under evaluation and the other designated as the base design for common comparison. The greater the index of difficulty associated with a design, the higher the required work effort, consequently resulting in a greater affect of the design on construction work.

Multiple ways of utilizing the index of difficulty to assess the effect of building design on construction activities are suggested. Additionally, application cases are exhibited to illustrate the implementation of the proposed approach and the required computations.

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NOTATIONS

$Aewe$	Average effective work effort
$Atplt$	Average total productive labor time required to carry out an activity for a construction part
$Atplt_B$	Average total productive time required to carry out an activity for a construction part with base design
$Celur$	Cumulative effective labor unit rate of a given construction activity for a set of construction parts
Cid	Cumulative index of difficulty, the index of difficulty of a set of construction parts for a given construction activity
$CidC$	Cumulative index of difficulty of a set of construction parts
Cpo	Cumulative produced output of a construction activity for a set of construction parts
$Elur$	Effective labor unit rate of a construction activity for a construction part
$Elur_B$	Effective labor unit rate of a construction activity for a construction part with base design
Id	Index of difficulty of a construction part for a given construction activity
IdC	Index of difficulty of a construction part
Po	Produced output of a construction activity for a construction part
Rid_C	Relative index of difficulty for crews
Rid_m	Relative index of difficulty for means and methods
Rid_f	Relative index of difficulty for a family of construction parts
Rid_g	Relative index of difficulty for a group of families of construction parts
RPo	Representative produced output for the construction part

RPo_B Representative produced output for the construction part with base design

GLOSSARY OF TERMS

Average productive time per unit of work. Constant of proportionality when there is a linear relationship between average productive time of a task and the quantity of work to be done in task.

Base construction part. The construction part with the base design for comparison purpose.

Building design. The product of the design process.

Design features. The expression of building design, they make buildings different from each other.

Effective labor unit rate. Labor unit rate calculate with productive time.

Effective work effort. Work effort calculates with productive time.

Labor unit rate. Total labor-hours spent in doing a work per unit of produced output.

Produced output. Output produced by construction activities.

Productive time. Effective working time of the construction crew; the time spent on the tasks necessary to carry out the construction activity.

Work effort. Labor hours spent doing work.

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

For quite some time, it has been widely recognized that building design impacts construction work[1]. Professionals in the construction industry have noted this phenomenon in the variations of cost and execution time of construction activities, owing to variances in the performance of crews working under similar conditions.

The very definition of buildability, which explicitly acknowledges the existence of this effect - the extent to which the design of a building facilitates the ease of construction (CIRIA, 1983)- aligns with findings from surveys administered to individuals within the construction industry. These surveys have identified design (or related terms) as one of the factors influencing labor productivity. Moreover, in the development of predictive models, design features have also been incorporated as factors that impact labor productivity.

Gaining insights into the influence of design on construction work holds the potential to enhance construction practices significantly. Within the design process, a clearer understanding of how design choices influence construction work will emerge. During the planning stage, this knowledge can facilitate more accurate estimations of construction costs and timeframes. In the preconstruction phase, it becomes instrumental in supporting analyses related to buildability, constructability, and value engineering.

[1] In the context of this research, building design refers to the product of the design process and construction work is the work carried out in any construction activities.

Furthermore, in the construction stage, this understanding enables the establishment of more realistic performance expectations for construction crews.

Regrettably, comprehensive information regarding the influence of design on construction work remains limited. The principal and more prominently researched contribution to this field is the Buildable Design Appraisal System (BDAS) (Low, 2001), a scoring framework aimed at quantifying buildability. This system was formulated to quantify the potential impact of building design on labor utilization. Research concerning this framework has aimed to assess the overall effects of building design on labor productivity. However, despite providing numerical evaluations, this scoring approach relies on the experience and judgment of individuals rather than performance data. The measure of buildability is based on scoring indexes associated with the general attributes of the building, thereby excluding many design features unique to a particular building design.

To overcome this situation, a reliable approach is needed to obtain factual information about the effect of building design on the construction work that then could be transformed into knowledge to make informed decisions.

1.2 Research Objective

The main objective of this research was to develop an approach to establish and evaluate the effect of building design on construction work. The approach should ultimately provide a means to evaluate the effect of design on construction work separating the effects of other factors. To reduce subjectivity, a quantitative evaluation based on field data was required.

Based on the research objective the following research question was formulated: How to establish and evaluate the effect of building design on construction work?

1.3 Research Scope

Given the state of knowledge of the matter of study, this research is exploratory and conceptual in nature.

Decisions made during the design process define the features of the final product. The design features of a building, the expression of building design, is the object of study of this research. Decisions about materials are not considered of interest.

One of the primary or direct effects of building design on construction work can be observed in labor work. Side effects on cost and time will derive from this first effect. Based on this, the scope of the research has been set on the effect of building design on construction labor work.

1.4 Expected Contribution

The proposed approach must be considered instrumental in the aim to obtain knowledge about the effect of building design on construction work. It will be straight forward focusing on a construction activity to get better insights into the effect of design features of a construction part on the work effort needed to complete the activity. On site, given the better understanding of crew performance, the possibility of establishing unrealistic performance expectations for crews will be diminished. Consequently, it is anticipated that disputes and workforce demotivation will also decrease.

The proposed approach provides means to support construction control. Construction parts with the greatest effect on construction activities can be identified so more management attention and supervision can be set when they are worked on.

Many evaluations of the effect of different construction part designs are required to get insights about the effect of a particular design feature on the work effort spent to complete a construction activity. This knowledge then will be available as input for any activity that requires it (i.e., labor performance estimation, buildability analysis, cost estimation, etc.).

The specialized work and continuous effort for better performance make the subcontractors work the ideal candidate to implement the approach and get benefits. Also, of interest can be the contribution of the proposed approach to low-income housing projects promoted by governments. Given the limited economic capacity of potential owners, the main challenge for design is to get the best value at reduced cost. Better decisions can be made if the effect of design features on construction work can be related to construction cost.

CHAPTER 2

LITERATURE REVIEW

With the support of main research databases and search engines, a comprehensive literature review was undertaken to identify previous studies and discussions about the relationship between building design and construction work. No studies have been found that directly address how to establish this relationship and measure the effects.

Buildability, the extent to which design makes easy construction, and Constructability, the use of construction knowledge - in our case during design phase- to achieve project objectives, are related to the interest of our research. In some measure, both concepts relate design with construction work. Research in these subjects has been included in the literature review, seeking to know how design influence on construction process has been considered.

Bearing in mind that labor productivity is a measure of work performance, it has been examined research that relates design to labor productivity. This was done to discover how design had been linked to labor productivity. In addition, given that labor productivity is necessary for estimating costs, the studies that relate the design to the cost estimate have also been included in this review.

2.1 Buildability, Constructability, and the Effect of Design

The report “Buildability: An Assessment” was published in 1983 by the Construction Industry Research and Information Association (CIRIA) of the UK. This report defines buildability 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). This term is often used when evaluating the ease with which building designs can be constructed (Fox et al., 2002).

In a questionnaire survey of British constructors conducted by Horner and Duff (2001) (as cited in Jarkas & Bitar, 2012), buildability was identified as one of the most important factors affecting labor productivity. Years earlier, Dong (1996) (as cited in Jarkas, 2010e, 2010g), found a positive relationship between standardization and repetition of design features, and labor productivity. Dong (1996) (as cited in Jarkas, 2010e, 2010g) believes that design simplification is achieved through the implementation of rationalization, standardization, and repetition. In this context, according to Moore and Tunnicliffe (1994) rationalization is “the minimization of the number of materials, sizes, components or sub-assemblies,” and standardization is “a design philosophy requiring the designed product to be produced from those materials, components and subassemblies remaining after design rationalization has taken place”. Although CIRIA has stated that the application of rationalization and standardization provides site efficiency, predictability, and better value, no direction has been suggested on how to assess or quantify these benefits in measurable terms (Jarkas, 2010b, 2010e).

For measuring the potential impact of a building design on the usage of labor, the Building and Construction Authority of Singapore developed the Buildable Design Appraisal System (BDAS) (Low, 2001). The appraisal system computes the buildable score of a design from the structural system, the wall system, and other design constituents. The buildable score of the structural and wall system provides a macro appraisal of the complete structural and wall system of a building. Structural and wall systems are divided into subsets with a range of labor-saving indices. Indices are derived from undocumented site productivity studies on the various design systems; and represent the aggregated wisdom of a panel of experts (Poh & Pheng, 1998). The buildability of the design at the micro-level is examined with other design constituents. A description of the application of BDAS can be found in the work of Ying and Pheng (2007). In this system, the effects of design on site efficiency and productivity are evaluated considering the level of simplicity, standardization, and extent of the single integrated elements (Jarkas, 2010b, 2010e). Simplicity refers to the use of building construction systems and installation details, both uncomplicated. Standardization refers to the repetition of grids, component sizes, and connection details. Single integrated elements bring related components together to form a single element, the use of precast concrete external walls, curtain walls are examples of this kind of elements (Mbamali et al., 2005).

Low (2001) found empirical evidence to support the positive relationships between buildability, measured using the BDAS, and productivity, measured by means of the floor area constructed per man-day, correlating these two measures. This relationship suggests that buildings with higher buildable scores tend to achieve correspondingly higher productivity levels. However, as was stated by Low (2001), buildable scores do not account for differences in contractor ability to deliver a project. Project management skills of individual contractors also affect labor productivity.

Because site productivity is influenced by numerous factors apart from design, any attempt to establish an index aimed at encouraging higher site productivity must take multiple factors into consideration. The BDAS does not consider any project-related and site-related factors such as building category, project size, architectural options and features, story height, site (Poh & Chen, 1998).

A Buildability Assessment Model (BAM) has been developed for use in Hong Kong by adapting the Buildable Design Appraisal System of Singapore. The labor-saving indices from BDAS have been re-named as buildability indices to represent a wider objective than saving site labor alone. Based on an evaluation of the relative buildability of common construction systems, these buildability indices were compiled by interviewing experienced practitioners. Lam and Wong (2008) have found that there is inherent resistance hindering the smooth implementation of the BAM. Designers valuing aesthetics more than buildability and the lack of incentive conducive to buildability improvement would be the main reasons for that situation.

Jarkas (2010b, 2010e) has questioned the reliability of buildable scores based on the BDAS system. The BDAS buildable scoring system is based on inputs provided by government agencies, private consultants, and product manufacturers. The inputs included both personal and group experience and judgment (Dong, 1996, as cited in Jarkas, 2010b, 2010e). Jarkas (2010b, 2010e) argues that a score should be developed using scientific methods of measurement and analysis. Jarkas (2010g, 2010i) state that another major shortcoming of this appraisal system stems from the lack of rigor in developing the buildability assessment system. According to him, the approach was too general; impacts of buildability factors require investigations in far greater depth to establish and quantify their effects on labor productivity.

As stated by Yang et al. (2003), research efforts in buildability have involved documenting concepts, developing principles, and exploring ways to enhance buildability. These efforts have also included identifying barriers, quantifying costs, and benefits, as well as offering project-level models, approaches, and implementation guides.

Researchers have continued to work on identifying factors, developing guidelines, and employing innovative tools to enhance buildability in design. In 2020, Li and Samarasinghe analyzed previous research publications from eleven countries to determine the level of significance of factors influencing design buildability. As part of the research output, they developed clear designer guidelines in the form of a checklist to mitigate building issues during the design stage. This checklist includes key elements outlined in the BCA: standardization, simplicity, and single integrated elements.

Poirriez et al. (2019) provide an example of how they guided the design of a 50 m span freeform steel roof to fully consider its buildability. Despite the complex geometry, all steel members were transformed into plates and single radii, making them comprehensible for the fabricator. The geometry of the edge beam sections, initially composed of conical surfaces, was rationalized through parametric modeling to consist solely of cylindrical surfaces. These surfaces are developable and thus easy to fabricate.

Buildability was incorporated as an objective function in a multi-objective structural design optimization of reinforced concrete foundations for wind turbines, based on data from a large Swedish wind farm project (Mathern et al., 2022).

More recently, from the perspective of construction students, Samarasinghe and Piri (2022) have found that virtual reality models offer significant advantages for assessing design buildability. The visual models notably improved the comprehensibility of complex designs, aiding in the identification and management of design buildability.

Constructability, a concept similar to buildability, is widely used and favored in United States (Jarkas, 2012a, 2010d). 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).

To facilitate the implementation of the constructability in the construction industry, the Construction Industry Institute (CII, 1993) developed a set of constructability concepts, grouped into the three main phases of the construction project: conceptual planning, design and procurement, and field operations. However, as pointed out by Pulaski and Horman (2005), it is not enough to know what generic concepts can be applied in each phase of construction project to understand which type of information is necessary to support design decisions.

Research in Constructability has focused on identifying constructability concepts, describing broad areas of concerns, and developing constructability improvement approaches and programs. Fischer and Tatum (1997) have presented a brief description of some of this work. These researchers found that:

- Much of the constructability background focuses on constructability during construction planning and construction operations, with less attention to construction input to the design process.
- Constructability knowledge is available but fragmented, difficult to get, and even more difficult to apply at critical points when design decisions are made.

- Constructability knowledge has been mainly available in the form of general guidelines, and these do not always specify precise constraints related to some design variables, and completely lack guidance regarding other variables.
- There is no structure available to link constructability knowledge to the design process and change the focus of design decisions.

To assist project teams in addressing constructability issues at the appropriate stages of the design process, Lee et al. (2018) proposed an approach that integrates constructability activities related to temporary work into the design phase of high-rise concrete buildings. Raviv et al. (2022) identified constructability methods and tools that should be applied during the early stages of project design to prevent specific constructability failures within the project context. They concluded that managerial approaches, such as assigning a constructability champion, facilitating early involvement of the general contractor in the design process, and enhancing design quality control, are the most effective methods for preventing constructability problems. Conversely, methods such as company procedures and owner involvement were found to be the least effective.

According to Glavinich (1995), the constructability of a design holds a qualitative nature, which makes it difficult to measure objectively. Furthermore, conclusions drawn from historical data on unique construction projects may not be reliable. However, despite this complexity, some studies have successfully related design features with constructability under specific conditions.

O'Connor et al. (1987) identified constructability concepts related to design features, such as simplified design configurations, standardization of elements, and modularization/preassembly. They also provided specific applications of these concepts focusing on electrical, instrumentation, piping, and structural projects.

Fischer and Tatum (1997) identified critical design variables, which are important for the constructability of a structure, particularly for major formwork construction methods. Such variables included dimensions of elements, distances between elements, changes in dimensions, and distance, among others. They also presented a classification schema for constructability knowledge and provided constructability guidelines and design rules.

Skibniewski et al. (1997) worked on the feasibility of a constructability computerized analysis of prefabricated beams in reinforced concrete frames using a machine learning approach. To conduct machine learning of the constructability decision rules, a collection of attributes and their values (nominal for simplicity) were used to characterize decisions regarding the problem under consideration. Based on their experience and the formal analysis of design cases, experts determined the constructability measure of designs -the dependent attribute. The produced decision rules were considered as acceptable by practicing engineers.

Navon et al. (2000) developed a model for rebar constructability diagnosis and correction. The Diagnosis Module analyzes a given design and alerts the structural engineer upon discovering a problem. The model can assist structural engineers by diagnosing designs and offering solutions for potential constructability problems, such as high congestion of reinforcement bars, collision between bars, and collision between bars and building systems.

One of the main approaches to improve constructability is through quantified assessment of designs. This enables an objective evaluation of constructability attributes (Wong et al., 2007).

Zin et al. (2004) have developed and validated a neural network model to assess beam design constructability. The model relates the level of application of main constructability principles during the design process with the level of design constructability. Historical project data sets related to beam construction were collected from various contractors. Their perceptions about the level of application of constructability principle and the corresponding level of design constructability were used to develop and validate the model.

Lee et al. (2013) have developed a constructability assessment model for international construction projects that can be used during the design and construction stages. The proposed model contains constructability influencing factors identified from interviews with experts and is based on structural equation techniques.

Chang, et al. (2017) have proposed an information theory-based model to assess the constructability of a truss structural design. The assessment was based on standardization and elements repetition at early design stages. In a design drawing, the graph of a truss structure can be expressed as a two-dimensional topological graph with points as joints and edges as struts. The model estimates the amount of information needed for construction based on uncertainty concerning assembly construction in the topological graph of the designed truss. The related entropy of uncertainty of the truss structure is taken as an index of constructability.

Zolfagharian and Irizarry (2017) developed a constructability assessment model for commercial building designs in the United States. The model structure follows BDAS approach, but with its own constructability indices for building components. Indices were obtained employing an analytic hierarchy process. Constructability attributes and common construction systems were identified from the literature review and interviews with construction professionals.

Zhang et al. (2016) have proposed a model that quantitatively assesses the constructability of a building design. The main factors affecting the constructability of building designs have been identified and incorporated in the model with relative weights using Analytical Hierarchy Process (AHP) technique based on a questionnaire survey. The platform for constructability assessment uses the building information model and 4D simulation model of the building project to provide information that allows assigning predefined values to each factor -utility values. The total constructability score is calculated as the weighted average of the utility values of factors.

Fadoul et al. (2020) have investigated how contemporary processes and object-oriented models can be used to provide a mechanism that represents the subjectivity of design constructability to inform decision making. They propose a BIM-based model using embedded information within the design environment to conduct the assessment. The modelling framework is composed of three key parts: The Constructability Model (CM) which formulates user-based knowledge; the BIM Design Model which provides required data for the assessment; and the Assessment Model (AM) which reasons with the formulated knowledge and the BIM Design Model. Using this framework, constructability related information can be captured and reasoned with to inform decisions at the early stages of the design process.

Information about the state of constructability practices and the efforts developed to improve constructability has been reported by Artidi (2002), Christodoulou et al. (2018), Darwish, et al. (2018), El Sayed et al. (2021), Mitropoulos, and Tajima (2022), Ospina, et al (2019), Pocock et al. (2006), Pulaski et al. (2006), Raviv at al. (2012), Wong et al. (2007), Zolfagharian and Irizarry (2017). Endeavors about quantitative measures of design from the point of view of its constructability, however, are few. Some of them have been reported.

In 2021, Nolan and Gibson conducted qualitative research to gain insights into the integration of constructability within the current design practices of UK construction design firms. They found that while the industry generally recognizes the importance of constructability, it is rare for designers to use formal policies or processes to integrate it into the design process. Instead, designers typically rely on their own tacit knowledge and experience when making subjective decisions about constructability, rather than using data-driven methods.

Buildability and constructability both seek to expand the utilization of construction experience during the design decision process. In both cases, general guidelines and heuristics principles are available. Few specific qualitative knowledge in support of design decisions is available, however, there is no clear quantification of the effect of design features on construction efficiency.

2.2 Effect of Design on Construction Labor Productivity and Cost Estimation

Studies on construction labor productivity can provide information on the influence of building design on construction labor work. More precisely, if the building design is considered a factor affecting construction labor productivity, a review of the literature focusing on the effects over this performance indicator can provide insights into the influence of building design on construction labor work.

Factors affecting construction labor productivity have been the topic of study of a large number of researchers (Abdul Kadir et al., 2005; Alinaitwe et al., 2007; Assaad et al., 2023; Borcherding & Alarcon, 1991; Dai & Goodrum, 2011, 2012; Dai, Goodrum & Maloney, 2007, 2009a; Dai, Goodrum, Maloney & Sayers, 2005; Dai, Goodrum, Maloney & Srinivasan, 2009b; Durdyev & Kandymov, 2018; El Gohary & Aziz, 2014; Enshassi et al., 2007; Hanna & Iskandar, 2018; Hasan et al., 2018; Jarkas & Bitar, 2012; Kazaz & Acikara, 2015; Kazaz, Acikara & Er, 2016; Kazaz, Manisali & Ulubeyli, 2008; Kazas & Ulubeyli, 2007; Kazaz, Ulubeyli, Acikara & Er, 2016; Korde et al., 2005; Lee et al., 2023; Liberda, et al., 2003; Mahamid, 2013; Momade et al., 2023; Moselhi & Khan, 2012; Naoum, 2016; Naoum et al., 2009; Rathnayake & Middleton, 2023; Rivas et al., 2010; Rojas & Aramvareekul, 2003; Seadon & Tookey, 2019; Shoar & Banatis, 2019; Tsehayae & Fayek, 2014a, 2014b; Toan et al., 2020; Van Tam et al., 2021). The goal of most of these studies was identifying, through interviews and surveys, the most relevant factors affecting labor productivity at project level.

Typically, published papers present factors affecting construction labor productivity identified from previous research. Some of them provide an extended revision of this topic (Borcherding & Alarcon, 1991; Lee et al., 2023; Tsehayae & Farek

2014b; Van Tam et al., 2021) or are really a state-of-the-art review (Hasan et al., 2018; Korde et al., 2005; Momade et al., 2023; Naoum, 2016). From the review of these studies, were found the following factors that affect labor productivity and whose scope includes building design:

- Constructability (El Gohary & Aziz, 2014)
- Design and buildability related issues (Naoum, 2016)
- Design complexity (Alinaitwe et al., 2007; Kazaz et al., 2008; Kazaz, Acikara et al., 2016; Toan et al., 2020; Van Tam, 2021)
- Design complexity level (Hasan et al., 2018; Jarkas & Bitar, 2012)
- Poor buildability design (Durdyev & Kandymov, 2018; PF Kadir et al., 2005)
- Project complexity (Durdyev & Kandymov, 2018; Liberda et al., 2003; Naoum et al., 2009; Tsehayae & Fayek, 2014b)

The review of similar research published in English language on the World Wide Web confirms other studies, mainly from 2012 onwards, where design is considered a factor that affects labor productivity. The terms used to refer to this factor include design complexity, design difficult to construct, design complexity level, complex design, and complexity in design.

The findings of these studies revealed a lack of consensus within the construction industry regarding the impact of design on labor productivity. This divergence in opinion can be attributed to a variety of factors, including cultural distinctions, varying project roles, the presence of union or nonunion workers, project performance, the current developmental stage, and several other contributing reasons.

Researchers have been working on the development of labor productivity models for construction activities mainly using artificial neural networking, fuzzy expert system, and simulation (AbouRizk et al., 2001; Al Refaie et al., 2021; Choy & Ruwanpura, 2006; Ebrahimi et al., 2021; El Gohary et al., 2017; Fayek & Oduba, 2005; Golnaraghi et al., 2020; Heravi & Eslamdoost, 2015; Lu et al., 2000; Muqeem et al., 2012; Muqeem et al., 2011; Nojedehi & Nasirzadeh, 2017; Nguyen et al., 2023; Song & AbouRizk, 2008; Sonmez & Rowings, 1998; Rowings & Sonmez, 1996; Thomas & Yiakoumis, 1987; Tsehayae & Fayek, 2016a, 2016b; Watkins et al., 2009). In a bibliometric review, Lee et al. (2023) have identified the most employed approaches for predicting labor productivity.

Using this modeling tools and regression analysis, research on labor productivity has focused on establishing the impact of a particular factor driving labor productivity. Absenteeism and turnover, building floor, construction changes, delivery methods, extended overtime, occasional overtime, scheduled overtime, fabricator, human parameters, motivation, overmanning, schedule compression, shift work, training, weather, workforce management, among others have been studied in this context, but design as a factor has not received attention. When researchers were interested in the effect of a factor on cumulative labor productivity, the study was conducted at the project level. Labor productivity data was gathered from projects in which the study factor was present at different levels. The study was carried out at the activity level when the factors showed variations during the project execution. Daily productivity data was collected and screened to avoid days with disruptions. In both studies, most of the time, the independent variable was not labor productivity, instead some relative measure of the actual productivity deviation from the estimated or baseline productivity was used.

Researchers have also shown interest in predicting the labor productivity of specific construction activities. After identifying the factors that influence labor productivity, multivariable predictive models were developed based on field data. However, only a small number of studies have included design features as contributing factors in these models.

In their research, Smith and Hanna (1993) reported the quantitative effects of certain design features on formwork labor productivity, as determined by Thomas et al. (1991) (cited in Smith & Hanna, 1993). They also provided examples of the impact of engineering design on wall formwork productivity using a predefined set of walls. To ensure accuracy, they examined daily labor productivity, excluding instances influenced by external factors.

Thomas and Sakarcan (1994) forecast labor productivity for masonry activity using the factor model developed by Sanders and Thomas (1991) for masonry daily productivity. In this model, factors that affect labor productivity are grouped into two main categories, one related to the work environment and the other with work to be done. Building design-related factors are considered in this latter group. This model requires the estimation of productivity for standard conditions and incorporates the effect of condition variables on labor productivity. It also takes into account quantitative sub-models that relate labor productivity with the presence of quantitative factors e.g., weather. In this approach, design features are considered as condition variables. Some of them directly affect the labor productivity model, and others are part of a group of conditions mutually exclusive (only one in the group is present). As productivity is evaluated on a daily base when more than one exclusive condition variable of the same group is present on a day or any variable is partially present, the decision about which variable consider or not depends on the major presence during the day. For forecasting purposes, Thomas and Sakarcan, (1994) suggest that productivity predicted with the factor model be corrected to reduce the gap with the actual productivity adding a constant value, the difference between predicted and actual productivity at a given point of time.

Jarkas has investigated (Table 1) the effects and relative influence of buildability factors on formwork, rebar, and concrete labor productivity in different elements. At macro and micro level, the effects were analyzed using multiple regression methods and categorical interaction-regression methods. Relative influence was determined through standardization of regression coefficients of the independent variables. Buildability factors were identified by Jarkas. Many of these (see Table 1) are results of design decisions.

To avoid masking or overshadowing the buildability effects by other factors, the construction projects selected shared common features. In an effort to minimize the negative influence of interruptions and disruptions on labor productivity, any significant delays encountered during the forming process were recorded and discounted.

Data was collected using intermittent and direct observation techniques. It was cross-checked and screened for possible measurement errors or outliers. The reliability of the regression relationships was determined by conducting statistical significance tests at 5% significance level. Strong correlations and high determination coefficients were found between the factors studied and labor productivity.

Table 1

Buildability Factors Affecting Labor Productivity from Jarkas Studies

Activity	Element	Factors	Study
Formwork	Edge floor	Depth of slab being edge-formed, slab geometric factor, type of formwork material used	(Jarkas, 2010a)
Formwork	Building floor	Variability of beam sizes, repetition of floor layout, floor area, average slab panel area, intersection of beams, beam–floor area ratio, percentage of curved beams and nonrectangular slab panels	(Jarkas, 2010b)
Formwork	Isolated foundations	Grid patterns, variability of foundation sizes, total surface area, average surface area	(Jarkas, 2010c)
Formwork	Walls	Shutter surface area, number of angles formed along the wall perimeter	(Jarkas, 2010d)
Formwork	Slab panels in building floors	Interaction effects of repetition, panel areas, geometry of panels	(Jarkas, 2010e)
Formwork	Grade beams	Variability of beam size, beam sizes, number of joints formed at beams intersections	(Jarkas, 2010f)
Rebar	Beamless slabs	Rebar diameter, reinforcement quantity, slab geometry, reinforcement layer location	(Jarkas, 2010g)
Rebar	Isolated foundation	Foundation sizes, rebar diameter, quantity of reinforcement fixed	(Jarkas, 2010h)
Rebar	Beams	Beam sizes, rebar diameter, stirrups diameter, reinforcement quantity, beam dimensions, span geometry	(Jarkas, 2010i)
Rebar	Beam-supported slab panels	Slab panel area, rebar diameter, quantity of reinforcement, panel geometry	(Jarkas, 2010j)
Formwork	Columns	Grid patterns, variability of column sizes, repetition, total and average shutter size, geometry of columns	(Jarkas, 2010k)
Formwork	Beams	Beam repetition, beam size, intersections, span geometry	(Jarkas, 2011)
Rebar	Walls	Bar diameter, total quantity of reinforcement installed, wall thickness, reciprocal of wall radius, plan geometry	(Jarkas 2012a)
Concreting	Horizontal and vertical elements	Concrete workability, reinforcing steel congestion, volume of pours, height relative to ground level	(Jarkas, 2012b)
Rebar	Columns	Variability of column sizes, rebar diameter, reinforcement quantity, geometry column section	(Jarkas 2012c)
Formwork	Walls	Perimeter configurations, plan geometry, curvature intensity, surface area	(Jarkas, 2012d)
Formwork	Building floors	Variability of beam sizes in the floor, usable floor area, number of beams used to support the floor area, number of individual slab panels formed within the floor due to beam-framing plan, number of joints formed due to beam intersections, floor configuration repetition criteria, number of angles formed around the floor perimeter.	(Jarkas 2016)

Although, there have been advances in knowledge about relationship between design features and labor productivity, particularly with Jarka's work, a formal theoretical explanation of the relationship between building design and construction labor work has not been developed.

A few research endeavors, focused on design features, have sought to identify their influence on labor productivity and cost.

Munshi (1992) (as cited in Jarkas, 2010g), explored the effects of geometry and openings configurations of block wall panels and, in comparison with plain walls, determined a significant average loss in labor productivity associated with constructing corners and openings.

Williamson (1999) (as cited in Jarkas, 2010g), investigated the relationship between design complexity and construction productivity. The complexity level of design 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. He concluded that as the complexity of the design increases, the difficulty at the task level increases and as a consequence, labor productivity decreases.

Wiezel and Oztemir (2003) studied the influence of two levels of design on construction productivity in the area of installing manufacturing tools in cleanroom facilities. In their work, the adopted design decisions were associated with design methods. The regression analysis performed provided a correlation between expected productivity and the design method utilized. The result demonstrated indirectly the relationship between design decisions and labor productivity.

Through a case study, Lerche et al. (2022) investigated the performance of two companies involved in the installation of cables with comparable configurations, each implementing their respective technical design solutions. Considering the uniformity of the surrounding environment, their findings showed the direct influence of design choices on the overall levels of productivity.

From de perspective of research on project cost, Akintoye (2000) study found the complexity of the project and buildability are among the main factors affecting cost estimating practice in the United Kingdom. This information was obtained in a survey about factors considered by construction contractors in cost estimating practice. In the context of this research, project complexity includes the type of structure, scale, and scope of construction, the complexity of the design, site constraints, and expected project organization. Akintoye (2000) has stated that these variables have direct consequences on the production performance on site.

Since the early 2000s, Staub-French and her collages pursued research to support the incorporation of building design in the cost estimation process. Staub-French and Fischer (2003) stated that it is a cost estimator's task to determine how a building design influences construction cost. This challenging task requires that estimator identify the design condition that affect the project's activities, resources, and resource productivity rates when configuring a cost estimate for a particular design (Staub-French, Fischer, Kunz, Ishii & Paulson, 2003).

The estimator selects a base productivity rate for each activity based on the crew composition and adjusts the base crew productivity rate to reflect the production impact of specific design conditions (Staub-French et al., 2002). Estimators have different preferences for when a crew's productivity rate is appropriate in a given activity and how it should be adjusted for different design conditions (Staub-French, Fischer, Kunz & Paulson, 2003).

This group of researchers has developed a framework for the cost estimating process to incorporate estimator rationality. While their contribution is useful for the estimating process, it is missing specific support to identify design conditions and quantify its effect on labor productivity.

Lowe et al., (2007) have investigated the influence of design-related variables on construction cost. Regression analysis and neural network modeling were applied to data from United Kingdom construction projects to produce cost models. Both techniques compare favorably with traditional methods of cost estimation (Lowe et al., 2007). Design related variables considered in these models are at the macro level and represent different construction systems and structural materials, no specific design features were considered.

2.3 Discussion

This review has found no research seeking to develop an approach to establish the effect of building design on construction work. Since construction labor productivity is a measure of construction work performance, the review has examined studies that could relate building design to labor productivity.

Buildability assessment systems have been developed to measure the potential impact of building design on the usage of labor. Buildability is measured based on scoring indices related to the general characteristics of the building. Thus, many design features, specific to a building design, are not considered. Although the assessment provides a numerical value, the scoring system is based on the experience and judgment of people and not on performance data like labor productivity A positive correlation between buildability scores and overall productivity can be expected, suggesting that greater buildability corresponds to higher productivity. However, it is important to note that the categorical model developed for the buildability score does not function as a predictive model for labor productivity.

Quantified assessment of designs allows an objective evaluation of constructability attributes. The research interest in this area has been directed towards the development of constructability assessment models. These are very diverse, in scope, variables, and model approach. In one end, the model can be for constructability of building elements, and in the other end for constructability of international projects; variables can be constructability principles, or factors influencing constructability o even corresponding equivalent variables like ones set in Chang et al. (2017) research. Models can be based on numerical relationships among perceptions, expert opinion for the relevance of categorical variables, or on formulations from other knowledge areas. From these developments, it is not clear how to establish the effect of building design on construction work, even more so, considering that a quantitative relationship between constructability and labor productivity has not been proposed.

Some research on the factors affecting labor productivity has identified design (or related terms) as one of them. Most of these studies based their findings on the perception of construction industry people, collected through surveys. Results show that there is no consensus about design relevance on labor productivity. Moreover, there is a gap when these results are compared to field data. Indices of relevance related to the factors are proper for comparison purposes and for establishing rankings, but they do not correspond to different levels of labor productivity. Given that these studies focus on labor productivity at the project level, their main focus is to determine which factors have a greater effect on labor performance. Unfortunately, design features were not considered, so it is not possible to establish how design features affect labor productivity from these studies.

In research aimed at determining the effect of a factor on labor productivity, building design has not yet been considered of interest. Based on this research approach, at the project level, any building design will require a value be assigned so that the effect on cumulative labor productivity can be explained by the values of building design. Moreover, any building design needs to be defined by a set of design features. At the construction activity level, as is common in many of these studies, a baseline daily productivity estimation is required. Deviations of actual daily productivity with respect to this baseline are explained by variations in the studied factor when there are no disruptions. On one hand, under this approach, building design needs to be expressed on a daily base, this latter can have some effect in the way of daily productivity must be measured. On the other hand, establishing the baseline productivity will require to define a base condition for building design, considering the development of construction work during project execution. An interesting point from this area of research: there are alternatives for measuring the effect of a factor on construction work. Many have considered relative measures of labor productivity.

Design features have been incorporated into models intended to forecast labor productivity in construction activities through data correlation. The results suggest that these models can be used to establish a relationship between design features and labor productivity. However, there is no clear guide for identifying design features to be incorporated into these models. In the studies that have been conducted, design features were established by researchers without providing a procedure for identifying the design features that represent building design.

While research in various domains has considered the relationship between building design and labor productivity, current advancements do not provide a straightforward method for measuring the impact of building design on construction work. There is a lack of a formal rational approach and guidelines to reach this objective.

CHAPTER 3

METHODOLOGY

The following is a description of the activities carried out to achieve the objective of the research. The overall process was not strictly sequential, modifications to previous developments were necessary to better adapt to the new formulations.

3.1 Preliminary Research Phase

An initial literature review was conducted, focusing on the defined object of study – the influence of building design on construction work. This systematic review resulted in the formalization of the research's focus on assessing the effect of building design on construction work. Additionally, a preliminary definition of the research problem was introduced at this stage.

The state of knowledge of the matter of study defined the exploratory and conceptual nature of the current research.

3.2 Formal Research Phase

Literature Review

A comprehensive literature review was undertaken to identify previous studies and discussions related to the subject of study. Main research databases and search engines were used for this purpose.

Research Objective Definition

The final problem statement was described and then the research objective and the research question to guide this study were defined.

Approach Development

To achieve the research objective, the proposed approach was developed, guided by deductive reasoning that draws upon the existing body of knowledge, established principles, recognized procedures, as well as observations and facts. Given the process-oriented nature of this research, the focal points of analysis were discrete entities associated with the subject of research, rather than centered on data.

An initial analysis of the problem was made in order to clarify its implications. Entities related to the problem were identified and the relationship between them was established. As a result of this process, the research objective was formulated in more precise terms. The goal was to provide a detailed picture of the subject under study, so the research at this first stage was rather descriptive.

In the second stage of development, an analysis was made in order to answer the research question. This was objective, systematic, and structured. A fundamental answer was provided and the reasoning behind it was used to develop means for the evaluation of the design effect on construction work. For this purpose, mathematical formulations were developed following a deductive approach.

The third and final stage was focused on concept development in closer areas to the object of study. Additional analysis was made based on the fundamental answer to the research question exploring ways to extend its application.

Applications Cases

The proposed approach was implemented in purposive application cases to show how the evaluation of design effect on construction work is made. Data used for this purpose was obtained from primary and secondary sources.

CHAPTER 4

ESTABLISHING THE EFFECT OF BUILDING DESIGN ON CONSTRUCTION WORK

4.1 Expressing Building Design

Design implementation produces a project to meet the owner's needs and expectations (Glavinich 1995). Design is regarded as an exercise seeking to provide a solution to a particular set of client requirements. Hence, design is a series of choices and decisions (RICS, 2000 cited in Lam et al., 2006).

Design decisions can be classified based on their scope from a high to a low level: 1) those addressing the building or system as a whole unit, 2) those for a group of parts, and 3) those for a single part. These decisions define the final product; therefore, the design features of a building are the expression of building design, they are what make one building different from another. Ultimately, these features will be those that affect construction work to a greater or lesser extent. So, building design is defined by the design features of the building.

Building design is the independent variable in this study. It should be considered as an n-dimensional variable composed of the n features that define it. Since not all design features can be expressed quantitatively or continuously, building design can be considered as a discrete qualitative n-dimensional variable.

If x_i describes a design feature of the building, building design (BD) is defined by:

$$BD = (x_1, x_2, \ldots, x_n)$$

Therefore, the effect of building design on construction work depends on the design features of the building. Or in other words, the effect of building design on construction work is the effect of the building design features on construction work.

Any construction product has construction components or parts (e.g., foundations, columns, walls, beams, etc.). Regardless of the decision process, the final product -the building design- is such because of the features of their parts. So, the design features of a construction part - shape, dimensions, patterns, among others- can be taken as the final expression of a building design, they make the whole product unique.

Design features can be arranged by construction parts in subsets so building design can be expressed by the design features of the construction parts of the building. That is, if X_i is the subset of design features of the construction part i.

$$X_i = (x_{i\,1}, x_{i\,2}, \ldots, x_{i\,ni})$$

Where $x_{i\,j}$ describes the design feature j of the construction part i and ni is the number of design features of construction part i.

Then BD can be expressed as:

$$BD = (X1, X2, \ldots, X_{np})$$

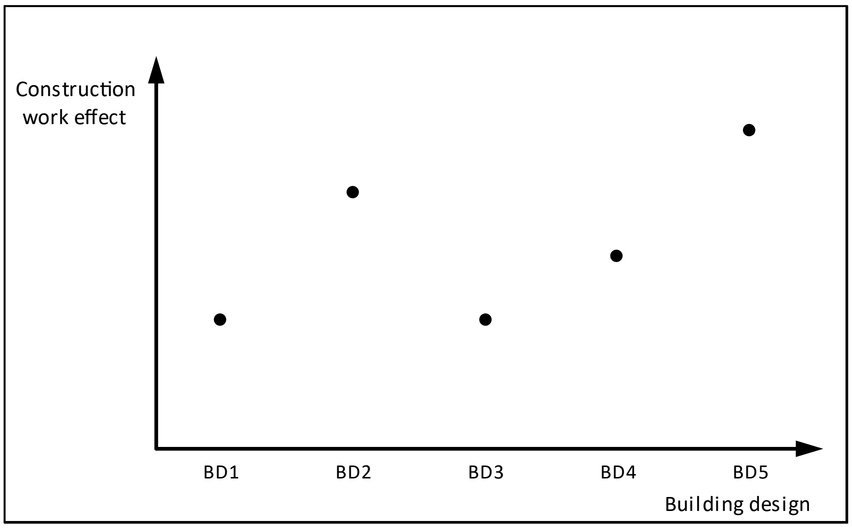
Where np is the number of construction parts

In the end, the effect that building design has on construction work is determined by how the design features of the construction parts of the building affect the construction work.

For the representation of the effect, however, any building design can be considered as a single entity, different from another due to the design features of its parts. Under this consideration, Figure 1 shows a representation of the building design effect on construction labor work. The position on the X-axis is arbitrary, it refers to different building designs. As shown in Figure 1, different building designs – BD1and BD3- can have the same effect on construction labor work.

Figure 1

Representation of the Effect of Building Design on Construction Labor Work



4.2 Expressing the Effect on Construction Labor Work

It has been widely recognized that building design has a significant impact on construction performance (HMSO, 1964; RCF, 1998; cited in Fox et al., 2002). Although polled expert opinion (Delphi method) could be used to evaluate the effect of design on construction work performance, approaches of this kind tend to be general, subjective, and cannot be applied to any particular building design. To increase its reliability, the evaluation of the effects of building design should be quantitative and supported by field data.

As was stated, the effect of building design can be assessed by examining the effect of the design of the construction parts of the building. Consequently, the effect of building design on construction work can be seen in the work carried out to build any construction part of the building. As to build any construction part, a series of construction activities is required, the effect of building design on construction work can be observed in the work done in the construction activities required by any construction part of the building. Finally, as this work is performed by crews, it can be concluded that building design affects the work carried out by crews.

One of the primary or direct effects of any factor affecting construction work can be observed in labor work. Cost and duration will be influenced by this first effect. Research attention has been focused on labor productivity to evaluate the effect on labor work. Construction labor productivity, expressed as the ratio of output (units produced) to input (total labor-hours), deals with the efficiency of the labor component of the construction processes (Tsehayae & Fayek, 2014a). Greater productivity means more produced output for the same amount of input (total labor-hours).

Labor productivity is influenced by numerous factors apart from design. Any attempt to establish its effect should aim to keep variations of other factors controlled. Problems arise with factors that, by nature, are not controlled, as well as with any work condition, like the management skills of the contractor, that can produce interruptions and disruptions.

The labor unit rate, the inverse of the previous definition of labor productivity, is also a measure of labor performance (Thomas, 2015). The labor unit rate is the measure of the total labor-hours spent doing a work per unit of produced output. It is also expressed as the work effort spent in doing a work per unit of produced output (the work effort is the total amount of labor-hours). In this case, a greater labor unit rate means more work effort spent for producing the same output. It is not properly a direct measure of efficiency it is rather a measure of the difficulty of performing a work. For the same produced output, an increment in the labor unit rate means more labor-hours, more work effort, more difficulty to accomplish the work. This performance indicator, as already noted, can show the effect of building design on crew members' work.

There is a direct relationship between the labor unit rate and the labor time to complete a work. This is convenient because labor unit rate computation requires just figuring out the time that all crew members spend doing the work – the labor time-.

Studies of factors that affect craft time utilization have rarely been reported in the literature (Yi & Chan, 2014). 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 & Ellis, 1990 cited in Jarkas 2010k). Total time is 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 (Jarkas 2010k).

Hence, productive time must be used to measure the effect of building design on crew work. It expresses the effective working time spent by crew members. Under this condition, the effective work effort is defined as the total productive time spent on the tasks necessary to carry out the construction activity. This is the total productive labor time. Rework time must be excluded. It represents a management issue. The labor unit rate calculated with the total productive labor time will be called hereinafter "effective labor unit rate" ($Elur$). This is the proposed parameter to express the effect of building design on construction labor work.

Given a construction part, for any of its construction activities, the effect of building design on construction work will be related to the greater or lesser effective labor unit rate of the construction activity. If a greater or lesser effective labor unit rate of construction activity is associated with a greater or lesser difficulty in completing a construction activity, then it can be concluded that the effect of building design on construction work is related to the difficulty a crew has in completing a construction activity.

4.3 Establishing the Effect of Building Design on Construction Labor Work

Traditionally, building designs focus on aesthetics, spatial layouts, and functionalities, with little emphasis on construction production aspects. Construction is left to the contractors who are supposed to match the construction process with design needs (Griffith & Sidwell 1995 cited in Lam et al. 2006). Design features drive the requirement for construction tasks (Staub-French, Fischer, Kunz & Paulson, 2003), so construction activities will be affected by the design features of the construction parts.

In the process of establishing the effect of building design on construction work, the focus of the study has been moved to the construction part and its design features. Any construction part can have many design features and require many construction activities. Instead of studying how one of these design features affects individually each construction activity, it is more appropriate to study how all design features of a construction part affect one construction activity. That is because all the design features of a construction part express the building design and give the part its identity.

The effect of building design on construction work can be assessed by examining how the design features of the construction parts of the building affect the related construction activities. And since the accomplishment of a construction activity requires the execution of construction tasks, the evaluation centers on the construction tasks required for executing a given construction activity.

Using the effective labor unit rate, building design effects on construction labor work can be evaluated based on the difficulty to carry out a work. The total productive labor time that a crew spends doing a work measured per unit of produced output is related to the greater or lesser difficulty of accomplishing the work. The total productive labor time needed to complete a construction activity depends on the productive time spent on the tasks required to complete the construction activity. Then the effective labor unit rate ($Elur$) can be expressed as:

$$Elur = \frac{t_1(q_1) + t_2(q_2) + \dots + t_n(q_n)}{Produced\ output} = \frac{\sum_{i=1}^{n} t_i(q_i)}{Po} \qquad (1)$$

Where for a given construction part and a construction activity:

$t_i(q_i)$ is the productive time of the task *i* required by the construction activity, it is a function of q_i

q_i is the quantity of work for task *i*

n is the number of tasks required by the construction activity

Po is the produced output, the amount of output produces by the construction activity

In its definition, by dividing the total productive labor time spent to complete a construction work by the amount of produced output, the effective labor unit rate eliminates the size effect.

Instead of measuring the quantity of output produced in a given period of time (hourly, daily, etc.) as in labor productivity studies, what is measured is the number of labor hours required to complete the activity (get the total produced output). Thus, the problem of using a fixed time frame as the analysis horizon when the produced output per unit of time is not constant can be overcome. Additionally, and even more relevant, the effect of the design on the construction work can be clearly evaluated.

Depending on how the design features affect the work tasks of a construction activity, crew members will have to spend more or less effective work effort to carry out the construction activity. The effective work effort is calculated by adding up the productive time required to accomplish the work tasks of the construction activity.

As the time to complete a task is not a deterministic variable, the effective work effort must be calculated as an average. This latter should be understood in the context that for a given construction part, if a crew works in a required construction activity infinite times the average effective work effort spent ($Aewe$) converges to one value, the mean of an infinite population.

Then, the effective labor unit rate must be reformulated as a mean value. An estimator of this value for a sample of m observations is obtained dividing the average effective work effort or what is the same the average total productive labor time ($Atplt$) by the produced output. For a given construction part and a construction activity, $Atplt$ can be calculated as:

$$Atplt = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} t_{ij}}{m}$$

Where t_{ij} is the productive time of task *i*, required by the construction activity and corresponding to the sample *j*. *n* is the number of tasks required by the construction activity.

Swapping the order of summation

$$Atplt = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} t_{ij}}{m}$$

Since m is a constant, it can be introduced to the outer summation

$$Atplt = \sum_{i=1}^{n} \frac{1}{m} \sum_{j=1}^{m} t_{ij}$$

Then

$$Atplt = \sum_{i=1}^{n} \bar{t}_i$$

The average total productive labor time needed to calculate the effective labor unit rate can be obtained by adding the average productive time of the tasks required by the construction activity.

So, Equation 1 changes to:

$$Elur = \frac{\bar{t}_1(q_1) + \bar{t}_2(q_2) + \ldots + \bar{t}_n(q_n)}{Produced\ output} = \frac{\sum_{i=1}^{n} \bar{t}_i(q_i)}{Po} \qquad (2)$$

Where for a given construction part and a construction activity:

$\bar{t}_i(q_i)$ is the average productive time of task *i*, required by the construction activity

q_i is the quantity of work for task *i*

n is the number of tasks required by the construction activity

Po is the produced output, the amount of output produces by the construction activity

Equation 2 focuses the attention on the construction tasks, more precisely, on finding a relationship between the average productive time of a task and the quantity of work to be done. This level of observation provides better control over conditions that affect the total productivity labor time since the observations can be made independently for each task, outliers can be identified and observations from abnormal conditions can be excluded. Additionally, the variability resulting from changes in conditions that are not totally controlled is reduced by the use of an average values, their effects are balanced.

Conveniently, models obtained from observations and representing average behaviors can be used to express the relationship between the average productive time of a task and the quantity of work to be done. A linear relationship means that the average productive time of a task is directly proportional to the quantity of work to be done. In this case, the constant of proportionality will be the average productive time per unit of work.

Once the behavior of the average productive time of tasks is understood, is necessary to figure out the quantity of work to be done in each task to then estimate the average total productive labor time for any set of design features of the construction part.

A variation in the difficulty to carry out a construction activity due to design features will be a consequence of a variation in total productive labor time per produced output (variation in $Elur$) due to:

- A variation in the quantity of work to be done on a given task.

- A reduction or increment in the required tasks.
- A variation in time to perform a task per unit of produced output.

Whenever the effect of a new set of design features needs to be evaluated, possibilities of variation in total productive labor time such as those mentioned should be taken into account.

A linear behavior between the average productive time of each task and the quantity of work to be done in this task does not imply the same behavior between the average total productive labor time and the produced output (this is because the quantity of work to be done in each task can change at a different rate than the one for the produced output). The latter would lead to the fact that the effective unit rate would not be constant. Application case A (see Chapter 7) shows this behavior.

4.4 Calculating the Effective Labor Unit Rate

The calculated effective labor unit rate must be understood as an estimator of the mean effective work effort per unit of produced output spent by a crew working in a construction activity in order to build a construction part.

Follow the steps indicated below to calculate the effective labor unit rate:

1. Identify the construction tasks required by the construction activity.
2. For each task, find the relationship between the average productive time spent on a task and the quantity of work to be done.
3. For each task, calculate the quantity of work to be done.
4. Using the relationship found in step 2, calculate the average productive time spent in each task.

5. Calculate the average total productive labor time by adding the average productive time spent on each task.

6. Divide the average total productive labor time by the produced output to obtain the effective labor unit rate.

CHAPTER 5

EVALUATING THE EFFECT OF BUILDING DESIGN ON CONSTRUCTION WORK

5.1 The Index of Difficulty of a Construction Part for a Construction Activity

Owing to the sequential flow of design and construction, it is common for builders to grumble about the thoughtlessness of some designs, particularly of those that make the construction task more difficult (Lam et al. 2006).

The values of the effective labor unit rate ($Elur$) reflect the level of difficulty involved in carrying out a construction activity. These values are measures of the average effective work effort per unit of produced output required to build construction parts with different designs. So, it is possible to evaluate the effect of building design on construction work by comparing $Elur$ values. A proposed ratio, named index of difficulty (Id), measures how difficult it is to carry out a construction activity for a construction part with specific design features, in relation to carry out the same construction activity for a construction part with design features considered as the base of comparison (these features are the ones that define the base design). The index of difficulty is the ratio between the effective labor unit rate of a construction activity for a construction part with given design features, and the effective labor unit rate of the construction activity for a construction part with the base design ($Elur_B$). Then:

$$Id = \frac{Elur}{Elur_B} \tag{3}$$

The value of the index of difficulty can be associated with the effect of the design features of a construction part on a required construction activity. The value of Id means that the effect of the design features of a construction part on a construction activity is Id times the effect of the base design features of a construction part on the construction activity. The construction part with the base design will be called hereinafter "the base construction part".

As productive time spent on tasks depends on the crew (the skills of crews are not the same), the estimations of the average productive time of tasks must be done for the same crew. So, the index of difficulty values how much the design features of a construction part affect the work of a given crew. From here, it can be stated that the design effect on construction work could be different for each crew (see case B in Chapter 7). But an index of difficulty can also be calculated for a group of crews. What is needed is to calculate the average effective work effort ($Aewe$), that is the average total productive labor time, for any design of a construction part, taking information from the same group of crews. For a given construction part and a construction activity, a sample of m observations, and a group of *l* crews, the average total productive labor time ($Atplt$) is:

$$Atplt = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} \frac{1}{l} \sum_{k=1}^{l} t_{ijk}}{m}$$

Where t_{ijk} is the productive time of task *i* required by the construction activity and corresponding to sample *j* and crew k. n is the number of tasks required by the construction activity.

Swapping the order of the summation and the positions of the constants m and *l*

$$Atplt = \frac{\sum_{k=1}^{l} \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} t_{ijk}}{m}}{l}$$

From a previous development

$$\frac{\sum_{j=1}^{m}\sum_{i=1}^{n} t_{ij}}{m} = \sum_{i=1}^{n} \bar{t}_i$$

Then:

$$Atplt = \frac{\sum_{k=1}^{l}\sum_{i=1}^{n} \bar{t}_{ik}}{l}$$

Two inferences can be made from this expression:

i. Swapping the order of summation and introducing the constant l into the summation

$$Atplt = \sum_{n=1}^{n} \frac{1}{l} \sum_{k=1}^{l} \bar{t}_{ik}$$

From here it can be stated that the average effective work effort spent in a construction activity can be calculated by adding the average effective work effort spent in the construction tasks required by construction activity, so the $Atplt$ calculation is decoupled.

ii. Entering the expression in *Elur* calculation

$$Elur = \frac{\frac{\sum_{k=1}^{l}\sum_{i=1}^{n} \bar{t}_{ik}}{l}}{Po}$$

Changing the position of the constant Po

$$Elur = \frac{\sum_{k=1}^{l} \frac{\sum_{i=1}^{n} \bar{t}_{ik}}{Po}}{l} = \frac{\sum_{k=1}^{l} Elur_k}{l}$$

So, when $Elur$ is calculated for a group of crews, this is the average value of those of crews. The index of difficulty for a group of crews must be calculated under this consideration (see case B in Chapter 7).

For a given construction activity, if the crews working for a contractor make up the group, the index of difficulty is calculated at the contractor level. It expresses how difficult it is for a contractor (its crews) to accomplish a construction activity given the design features of a construction part. Under the same criteria, the index of difficulty could be calculated in a broader scope. In any case, and for any design, the average productive time of tasks must be obtained from the same group of crews. In other words, the estimated average productive time for each task must always represent the work effort spent by a single group (comparison is based on variations of work effort spent by this group due to design).

5.2 Evaluating the Effect of Design on Construction Work

Effect of the Design of a Construction Part on a Construction Activity

As was stated previously, the design features of a construction part are the ones that affect construction work. This effect is observable in the construction activities required to build a construction part, so the index of difficulty is calculated for any construction part and its required construction activities.

The indexes of difficulty can be arranged in a matrix $[Id]$ to express the difficulty of performing the construction activities for a given building design. This is:

$$[Id] = \begin{bmatrix} Id_{1,1} & Id_{1,2} & Id_{1,3} & \dots & Id_{1,j} & \dots & Id_{1,m} \\ Id_{2,1} & Id_{2,2} & Id_{2,3} & \dots & Id_{2,j} & \dots & Id_{2,m} \\ Id_{3,1} & Id_{3,2} & Id_{3,3} & \dots & Id_{3,j} & \dots & Id_{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Id_{i,1} & Id_{i,2} & Id_{i,3} & \dots & Id_{i,j} & \dots & Id_{i,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Id_{n,1} & Id_{n,2} & Id_{n,3} & \dots & Id_{n,j} & \dots & Id_{n,m} \end{bmatrix}_{n\times m}$$

n is the total number of construction activities. This dimension expresses the "how" of a construction project. Rows are associated with the construction activities.

m is the total number of construction parts. This dimension expresses the "what" of a construction project. Columns are associated with the construction parts.

The index of difficulty $Id_{i,j}$ corresponds to the index of the construction part j for the construction activity i. Because not all the construction activities apply to all the construction parts many of these indexes are zero.

$[Id]$ matrix can be expressed as:

$$[Id] = \begin{bmatrix} Id_{r1} \\ Id_{r2} \\ Id_{r3} \\ \vdots \\ Id_{rn} \end{bmatrix}_{n\times m}$$

Where $[Id_{ri}] = [Id_{i,1} \quad Id_{i,2} \quad Id_{i,3} \quad \dots \quad Id_{i,j} \quad \dots \quad Id_{i,m}]$ is a row matrix of $1 \times m$. It contains the indexes of difficulty for the construction activity i. Because not all construction parts require the construction activity i, some indexes are zero.

$[Id]$ matrix can also be expressed as:

$$[Id] = [Id_{C1} \quad Id_{c2} \quad Id_{c3} \quad \dots \quad Id_{cm}]_{n\times m}$$

Where $\left[Id_{cj}\right]^T = [Id_{1,j} \quad Id_{2,j} \quad Id_{3,j} \quad \dots \quad Id_{i,j} \quad \dots \quad Id_{n,j}]$. $\left[Id_{cj}\right]$is a column matrix of $n \times 1$. It contains the indexes of difficulty for the construction activities required by the construction part j. Because not all construction activities are required by construction part j, some indexes are zero.

A family of construction parts is a set of similar construction parts that require the same construction activities. Columns, beams, and walls of reinforced concrete (RC) are examples of families of construction parts. A subfamily of construction parts is any subset of construction parts from a given construction parts family. RC Columns on the first floor, RC columns on the second floor, and so on are examples of subfamilies of construction parts of the family of construction parts: reinforced concrete columns. Different criteria can be used to define a subfamily, in the example presented, the criterion was the floor on which the columns are located.

Construction Part, from a Family, with the Greatest Effect of Design on a Given Construction Activity

The effect of the design of a construction part, from a family of construction parts, on a given construction activity depends on the design features of this construction part. The relative magnitude of this effect can be evaluated with the index of difficulty.

Given a construction activity i, the indexes of difficulty of construction parts, corresponding to a family of construction parts, can be arranged in a row matrix $[Id_{Aip}]$, a submatrix of $[Id_{ri}]$. If s is the number of elements of the family, then:

$$[Id_{Aip}] = [Id_{Aip\,1} \quad \ldots \quad Id_{Aip\,s}]$$

$Id_{Aip\,\mathrm{j}}$ is the index of difficulty of a construction part j, from a family of construction parts, for a given construction activity *i.*

The sequence in which the construction part from a family is carried out allows, through its index of difficulty, to follow how the effect of design on the construction activity progresses during construction (see case A in Chapter 7). It is also possible to identify the construction part of the family whose design has the greatest effect on the work of a given construction activity. This will be the one in $\left[Id_{Aip}\right]$ with the highest index of difficulty. Both considerations can also be applied to a subfamily of construction parts.

Effect of the Design of a Family of Construction Parts on a Given Construction Activity

For a given construction activity, it is also of interest to determine the index of difficulty of a family of construction parts. This index named the cumulative index of difficulty (Cid) expresses the effect of the design of a set of construction parts on the construction activity. It is expected that this value depends on the index of difficulty of the construction parts and the produced output associated.

Based on the definition of the index of difficulty and considering that only one base design corresponds to a construction parts family, Cid is the ratio between the average effective work effort per unit of produced output spent working on the family of construction parts, and the average effective work effort per unit of produced output spent working on the base construction part ($Elur_B$).

If the cumulative effective labor unit rate ($Celur$) of a given construction activity for a family of construction parts is defined as the total average effective work effort per produced output spent working on the family of construction parts, then Cid is:

$$Cid = \frac{Celur}{Elur_B} \tag{4}$$

Let $Atplt_j$ be the average total productive labor time (that is the average total effective work effort) required for finishing the construction part j with a given design and Po_j the produced output of the construction activity for the construction part j. Then the cumulative effective labor unit rate for a family of construction parts is:

$$Celur = \frac{\sum_{j \in \{P\}} Atplt_j}{\sum_{j \in \{P\}} Po_j} \tag{5}$$

$\{P\}$ is the set of subindices that define the family of construction parts.

For a given construction activity, by definition, the effective labor unit rate for the construction part j ($Elur_j$) is:

$$Elur_j = \frac{Atplt_j}{Po_j}$$

And from here

$$Atplt_j = Elur_j \times Po_j \tag{6}$$

For a given construction activity, the index of difficulty of the construction part j (Id_j), is evaluated as:

$$Id_j = \frac{Elur_j}{Elur_B}$$

Then

$$Elur_j = Elur_B \times Id_j \tag{7}$$

Replacing (7) in (6) and rearranging

$$Atplt_j = Elur_B \times Po_j \times Id_j \tag{8}$$

Replacing (8) in (5)

$$Celur = \frac{\sum_{j \in \{P\}} Elur_B \times Po_j \times Id_j}{\sum_{j \in \{P\}} Po_j} = \frac{Elur_B \sum_{j \in \{P\}} Po_j \times Id_j}{\sum_{j \in \{P\}} Po_j} \tag{9}$$

Replacing (9) in (4)

$$Cid = \frac{Celur}{Elur_B} = \frac{\frac{Elur_B \sum_{j \in \{P\}} Po_j \times Id_j}{\sum_{j \in \{P\}} Po_j}}{Elur_B}$$

Finally

$$Cid = \frac{\sum_{j \in \{P\}} Po_j \times Id_j}{\sum_{j \in \{P\}} Po_j} \tag{10}$$

For a given construction activity, the cumulative index of difficulty (Cid) of a family of construction parts is equal to the weighted average of the indexes of difficulty of the construction parts. Weights are the produced output associated with the construction part (Appendix A shows a matrix calculation of this index).

The cumulative produced output Cpo of a construction activity associated with a family of construction parts is defined as:

$$Cpo = \sum_{j \in \{P\}} Po_j \tag{11}$$

Equation 10 can be also expressed in a more reduced way as:

$$Cid = \sum_{j \in \{P\}} w_j \times Id_j \tag{12}$$

Where w_j is defined as:

$$w_j = \frac{Po_j}{\sum_{j \in \{P\}} Po_j} = \frac{Po_j}{Cpo}$$

Reducing the scope of summation, the cumulative index of difficulty can be calculated for any set of construction parts from a family.

Cid can be used to measure the effect of the design of a set of construction parts, from a family, on a given construction activity.

Subfamily of Construction Parts, from a Family, with the Greatest Effect of Design on a Given Construction Activity

Given a construction activity i, if the construction parts from a family are grouped in subfamilies based in one criterion (for instance, if RC columns is considered a family, columns could be grouped in subfamilies based on the floor of the building where are they are situated, the cumulative index of difficulty can be calculated for each subfamily and arranged in a row matrix $\left[Cid_{Aip}\right]$. If t is the number of subfamilies, then:

$$\left[Cid_{Aip}\right] = [Cid_{Aip\,1} \quad \dots \quad Cid_{Aip\,t}]$$

$Cid_{Aip\,\mathrm{j}}$ is the cumulative index of difficulty of a subfamily j, from a family of construction parts, for a given construction activity *i.*

The subfamily from a given family whose design has the greatest effect on the work of a given construction activity is the one in $\left[Cid_{Aip}\right]$ with the highest cumulative index of difficulty (see example 4, later in this Chapter, for a numerical application).

Construction Activity Most Affected by the Design of a Given Construction Part

Different construction activities are required to build a construction part. The design features of this construction part affect the construction activities at different levels.

Given a construction part j, the indexes of difficulty corresponding to the construction activities really required by the construction part can be arranged in a column matrix $[Id_{Pja}]$, a submatrix of $[Id_{cj}]$. If u is the number of construction activities really required, then:

$$[Id_{Pja}]^T = [Id_{Pja\,1} \quad \dots \quad Id_{Pja\,u}]$$

$Id_{Pja\,i}$ is the index of difficulty of a given construction part j for a required construction activity *i.* In the definition above the matrix $[Id_{Pja}]$ is transposed to $[Id_{Pja}]^T$ only for the purpose of presenting its elements in a row rather than a column.

For a given construction part *j,* the required construction activity most affected by the design features is the one in $[Id_{Pja}]$ with the highest index of difficulty.

Construction Activity Most Affected by the Design of a Given Subfamily of Construction Parts

With respect to the previous case, the focus of the analysis moves from the effect of the design of a single construction part to the effect of the design of a subfamily of construction parts. In both cases, a similar approach can be used to identify the construction activity that is most affected by the design.

Given a subfamily of construction parts j, the cumulative indexes of difficulty corresponding to the construction activities really required by the construction parts can be arranged in a column matrix $[Cid_{Pja}]$. If u is the number of construction activities really required, then:

$$[Cid_{Pja}]^T = [Cid_{Pja\,1} \quad \dots \quad Cid_{Pja\,u}]$$

$Cid_{Pja\,i}$ is the cumulative index of difficulty of a given subfamily of construction part j, from a family of construction parts, for a required construction activity *i*

Among the construction activities required by a given subfamily of construction parts j, the activity most affected by the design features of the construction parts of the subfamily j is the one in $\left[Cid_{Pja}\right]$ with the highest cumulative index of difficulty.

Effect of the Design of a Construction Part on Construction Work

A set of construction activities will be required to build a given construction part. As design features of the construction part affect each construction activity it is of interest to evaluate the effect of the design of a construction part on all the work required by the construction part.

Based on the indexes of difficulty in $\left[Id_{Pja}\right]$, the index of difficulty of a construction part (IdC) is defined to evaluate the effect of the construction part design on the construction work.

The index of difficulty of a construction part is the ratio of the total average effective work effort per unit of produced output for two design conditions - one corresponding to the construction part under evaluation and the other corresponding to the construction part with the base design (the base construction part). The main problem here is that there is not a single produced output. Consider for instance a reinforced concrete (RC) column. This construction part requires at least three construction activities formworking, rebar, and concrete placing with surface, weight, and volume measurements to express the amount of work to be done. A measure per unit of output is required to handle the size effect. To overcome this problem a representative produce output must be defined e.g., in the case of the RC column, the volume of the column.

Taking into account that the average work effort spent on a construction activity is the average total productive labor time spent on the construction activity, the index of difficulty of a construction part (IdC) can be defined as:

$$IdC = \frac{\frac{\sum_{i\in\{A\}} Atplt_i}{RPo}}{\frac{\sum_{i\in\{A\}} Atplt_{B\,i}}{RPo_B}} \tag{13}$$

Where:

$Atplt_i$ is the average total productive labor time required to carry out the activity *i* for the construction part with a given design

$Atplt_{Bi}$ is the average total productive time required to carry out the activity *i* for the construction part with the base design

RPo is the representative produced output for the construction part with a given design

RPo_B is the representative produced output for the construction part with the base design

$\{A\}$ is the set of subindices that define the construction activities really required by the construction part.

From (8)

$$Atplt_i = Elur_{Bi} \times Po_i \times Id_i \tag{14}$$

Where:

$Elur_{Bi}$ is the effective labor unit rate of the required activity i for the construction part with base design

Po_i is the produced output of the required activity *i*

Id_i is the index of difficulty of the construction part for the required activity *i*

By definition

$$Elur_{B\,i} = \frac{Atplt_{B\,i}}{Po_{B\,i}}$$

Where $Po_{B\,i}$ is the produced output of the required activity i for a construction part with base design.

Then

$$Atplt_{B\,i} = Elur_{B\,i} \times Po_{B\,i} \qquad (15)$$

Replacing (14) and (15) in (13)

$$IdC = \frac{\frac{\sum_{i\in\{A\}} Elur_{Bi} \times Po_i \times Id_i}{RPo}}{\frac{\sum_{i\in\{A\}} Elur_{Bi} \times Po_{B\,i}}{RPo_B}}$$

Then,

$$IdC = \frac{RPo_B}{RPo} \times \frac{\sum_{i\in\{A\}} Elur_{Bi} \times Po_i \times Id_i}{\sum_{i\in\{A\}} Elur_{Bi} \times Po_{B\,i}} \qquad (16)$$

IdC can be used to measure the effect of the design of a construction part on construction work.

In case the construction part only requires one construction activity as it is expected the previous expression for IdC leads to a tautology:

$$IdC = Id$$

Construction Part, from a Family, with the Greatest Effect of Design on Construction Work

The design features of the construction parts affect the average effective work effort required by the construction activities.

If $[IdC_P]$is a row matrix of indexes of construction parts (IdC) corresponding to a family of construction parts and s is the number of elements of the family, then:

$$[IdC_P] = [IdC_{p\,1} \quad \dots \quad IdC_{p\,s}]$$

$IdC_{p\,j}$ is the index of difficulty of a construction part j from a family of construction parts.

The construction part, from a family, whose design has the greatest effect on construction work is the one in $[IdC_P]$ with the highest index of difficulty IdC_P.

Effect of the Design of a Family of Construction Parts on Construction Work

To extend the application of the index of difficulty of a construction part to a family of construction parts, the cumulative index of difficulty of construction parts *CidC* is defined. It expresses the effect of the design of a family of construction parts on construction work. This index can be evaluated as the ratio between the average effective work effort per unit of produced output spent in the work carried out on the family of construction parts, and the average effective work effort per unit of produced output spent in the work carried out in a construction part with the base design. This latter because only one base design is defined for the construction parts family.

On the basis that the average effective work effort $Aewe$ is equal to the average total productive labor time $Atplt$, the cumulative index of difficulty of construction parts $CidC$ can be expressed as:

$$CidC = \frac{\dfrac{\sum_{j\in\{P\}}\sum_{i\in\{A\}} Atplt_{i\,j}}{\sum_{j\in\{P\}} RPo_j}}{\dfrac{\sum_{i\in\{A\}} Atplt_{Bi}}{RPo_B}} \qquad (17)$$

Where:

$Atplt_{i\,j}$ is the average total productive labor time required to carry out the activity *i* for the construction part *j* with a given design

$Atplt_{Bi}$ is the average total productive labor time required to carry out the activity *i* of the construction part with the base design

RPo_j is the representative produced output for the construction part *j* with a given design

RPo_B is the representative produced output for the construction part with base design

$\{A\}$ is the set of subindices that define the construction activities really required by the construction part and $\{P\}$ is the set of subindices that define the family of construction parts.

From (8)

$$Atplt_{ij} = Elur_{Bi} \times Po_{ij} \times Id_{ij} \tag{18}$$

And from (15)

$$Atplt_{Bi} = Elur_{Bi} \times Po_{Bi} \tag{19}$$

Where:

$Elur_{Bi}$ is the effective labor unit rate of the required activity i for construction part *j* with base design

Po_{ij} is the produced output of the required activity i for the construction part *j* with a given design

Po_{Bi} is the produced output of the required activity i for the construction part *j* with the base design

Id_{ij} is the index of difficulty of the construction part *j* for the required activity *i*

Replacing (18) and (19) in (17)

$$CidC = \frac{\frac{\sum_{j\in\{P\}}\sum_{i\in\{A\}} Elur_{Bi} \times Po_{ij} \times Id_{ij}}{\sum_{j\in\{P\}} RPo_j}}{\frac{\sum_{i\in\{A\}} Elur_{Bi} \times Po_{B\,i}}{RPo_B}} \tag{20}$$

From (16)

$$\sum_{i\in\{A\}} Elur_{Bi} \times Po_{i\,j} \times Id_{i\,j} = IdC_j \times \frac{RPo_j}{RPo_B} \sum_{i\in\{A\}} Elur_{Bi} \times Po_{B\,i} \tag{21}$$

Replacing (21) in (20)

$$CidC = \frac{\frac{\sum_{j\in\{P\}} IdC_j \times \frac{RPo_j}{RPo_B} \sum_{i\in\{A\}} Elur_{Bi} \times Po_{B\,i}}{\sum_{j\in\{P\}} RPo_j}}{\frac{\sum_{i\in\{A\}} Elur_{Bi} \times Po_{B\,i}}{RPo_B}}$$

Simplifying

$$CidC = \frac{\sum_{j\in\{P\}} RPo_j \times IdC_j}{\sum_{j\in\{P\}} RPo_j} \tag{22}$$

$CidC$ is a weighted average of the indexes of difficulty of the construction parts. Weights are the representative produced output for the construction part j with a given design.

$CidC$ can be used to measure the effect of the design of a set of construction parts, from a family, on construction work.

Subfamily of Construction Parts, from a Family, with the Greatest Effect of Design on Construction Work

If the construction parts from a family are grouped in subfamilies based on one criterion (for instance, if RC beams is considered a family, beams could be grouped in subfamilies based on the cross sections dimensions), the cumulative index of difficulty of each subfamily can be arranged in a row matrix $[CidC_P]$. If t is the number of subfamilies, then:

$$[CidC_P] = [CidC_{P1} \quad \ldots \quad CidC_{P\,t}]$$

$CidC_{p\,j}$ is the cumulative index of difficulty of a subfamily of construction parts j from a family of construction parts.

The subfamily whose design has the greatest effect on the construction work is the one in $[CidC_P]$ with the highest cumulative index of difficulty.

5.3 Examples of Numerical Calculations of the Effect of Building Design on Construction Labor Work

Four construction activities and nine construction parts grouped into three families have been considered for the numerical calculations of the effect of building design on the construction work.

Family A includes construction parts 1, 2, 3, and 4, family B includes construction parts 5, and 6, and family C includes construction parts 7, 8, and 9.

Information corresponding to the design under evaluation is arranged in 4x9 two-dimensional matrices; rows are assigned for construction activities and columns for construction parts. The entries are organized in submatrices associated with the construction part families.

Let $[Po]$ be the matrix of produced output of the construction activities for the construction parts with design under evaluation:

$$[Po] = \left[\begin{bmatrix} 0.00 & 0.00 & 0.00 & 0.00 \\ 6.00 & 8.00 & 6.50 & 7.00 \\ 3.00 & 3.25 & 2.75 & 3.00 \\ 0.50 & 0.65 & 0.65 & 0.70 \end{bmatrix} \begin{bmatrix} 0.00 & 0.00 \\ 6.50 & 7.50 \\ 3.50 & 3.50 \\ 0.50 & 0.60 \end{bmatrix} \begin{bmatrix} 5.00 & 3.50 & 2.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \end{bmatrix}\right]_{4\times 9}$$

And $[Elur]$ the matrix of the effective labor unit rate of the construction activities for the construction parts with design under evaluation:

$$[Elur] = \left[\begin{bmatrix} 0.00 & 0.00 & 0.00 & 0.00 \\ 1.67 & 1.75 & 1.54 & 1.57 \\ 2.17 & 2.15 & 2.18 & 2.27 \\ 4.20 & 4.15 & 4.23 & 4.14 \end{bmatrix} \begin{bmatrix} 0.00 & 0.00 \\ 1.85 & 1.87 \\ 2.14 & 2.29 \\ 4.60 & 4.67 \end{bmatrix} \begin{bmatrix} 0.50 & 0.43 & 0.45 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \end{bmatrix}\right]_{4\times 9}$$

Information corresponding to the base design is arranged in a 4x3 two-dimensional matrix; rows are assigned for construction activities and columns for families of construction parts. The entries are organized in submatrices associated with the construction part families.

Let $[Po_B]$ be the matrix of produced output of the construction activities for the construction parts with the base design.

$$[Po_B] = \left[\begin{bmatrix} 0.00 \\ 5.00 \\ 2.40 \\ 0.40 \end{bmatrix} \begin{bmatrix} 0.00 \\ 5.50 \\ 2.75 \\ 0.45 \end{bmatrix} \begin{bmatrix} 2.00 \\ 0.00 \\ 0.00 \\ 0.00 \end{bmatrix}\right]_{4\times 3}$$

To simplify calculations, an expanded version of matrix $[Po_B]$ can be used. In this matrix, the number of rows remains the same, while the number of columns expands from the number of families to the number of construction parts. Each column of the matrix is assigned to a construction part, and the entries for the construction parts replicate the values corresponding to their respective families. The expanded version of matrix $[Po_B]$ will be of dimensions 4x9, as shown below:

$$[Po_B] = \left[\begin{bmatrix} 0.00 & 0.00 & 0.00 & 0.00 \\ 5.00 & 5.00 & 5.00 & 5.00 \\ 2.40 & 2.40 & 2.40 & 2.40 \\ 0.40 & 0.40 & 0.40 & 0.40 \end{bmatrix} \begin{bmatrix} 0.00 & 0.00 \\ 5.50 & 5.50 \\ 2.75 & 2.75 \\ 0.45 & 0.45 \end{bmatrix} \begin{bmatrix} 2.00 & 2.00 & 2.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \end{bmatrix}\right]_{4\times 9}$$

Let $[Elur_B]$ be the matrix of the effective labor unit rate of the construction activities for the construction parts with base design:

$$[Elur_B] = \begin{bmatrix}\begin{bmatrix}0.00\\1.50\\2.00\\4.00\end{bmatrix} & \begin{bmatrix}0.00\\1.70\\2.10\\4.50\end{bmatrix} & \begin{bmatrix}0.40\\0.00\\0.00\\0.00\end{bmatrix}\end{bmatrix}_{4\times 3}$$

Applying the same considerations as for matrix $[Po_B]$, the expanded version of matrix $[Elur_B]$ is:

$$[Elur_B] = \begin{bmatrix}\begin{bmatrix}0.00 & 0.00 & 0.00 & 0.00\\1.50 & 1.50 & 1.50 & 1.50\\2.00 & 2.00 & 2.00 & 2.00\\4.00 & 4.00 & 4.00 & 4.00\end{bmatrix} & \begin{bmatrix}0.00 & 0.00\\1.70 & 1.70\\2.10 & 2.10\\4.50 & 4.50\end{bmatrix} & \begin{bmatrix}0.40 & 0.40 & 0.40\\0.00 & 0.00 & 0.00\\0.00 & 0.00 & 0.00\\0.00 & 0.00 & 0.00\end{bmatrix}\end{bmatrix}_{4\times 9}$$

Example 1. Effect of the Design of a Construction Part on a Construction Activity

The indexes of difficulty of construction parts for their required construction activities can be calculated and arranged in a matrix $[Id]$. The elements of $[Id]$ are calculated as:

$$Id_{i,j} = \frac{Elur_{i,j}}{Elur_{B\ i,j}}$$

Then

$$[Id] = \begin{bmatrix}\begin{bmatrix}0.00 & 0.00 & 0.00 & 0.00\\1.11 & 1.17 & 1.03 & 1.05\\1.08 & 1.08 & 1.09 & 1.13\\1.05 & 1.04 & 1.06 & 1.04\end{bmatrix} & \begin{bmatrix}0.00 & 0.00\\1.09 & 1.10\\1.02 & 1.09\\1.02 & 1.04\end{bmatrix} & \begin{bmatrix}1.25 & 1.07 & 1.13\\0.00 & 0.00 & 0.00\\0.00 & 0.00 & 0.00\\0.00 & 0.00 & 0.00\end{bmatrix}\end{bmatrix}_{4\times 9}$$

$Id_{2,3} = 1.03$ values the effect of the design of construction part 3 on the construction activity 2.

Example 2. Construction Part, from a Family, with the Greatest Effect of Design on a Given Construction Activity

Consider the indexes of difficulty of construction parts for construction activity 2. The second row of $[Id]$ (see Example 1).

$$[Id_{r2}] = [[1.11 \quad 1.17 \quad 1.03 \quad 1.05] \quad [1.09 \quad 1.10] \quad [0.00 \quad 0.00 \quad 0.00]]$$

From there, the indexes of difficulty of construction parts of family A for construction activity 2 can be arranged on a row matrix $[Id_{A2p}]$.

$$[Id_{A2p}] = [1.11 \quad 1.17 \quad 1.03 \quad 1.05]$$

In Family A, the construction part with an Id = 1.17 (construction part 2) is the one whose design has the greatest effect on construction activity 2.

Example 3. Effect of the Design of a Family of Construction Parts on a Given Construction Activity

The effect of the design of the family of construction parts A on construction activity 2 can be evaluated with the cumulative index of difficulty of family A for construction activity 2 (Equation 10).

$$Cid = \frac{\sum_{j\in\{P\}} Po_j \times Id_j}{\sum_{j\in\{P\}} Po_j}$$

As was established in Example 2, the row matrix of indexes of difficulty of construction parts of family A for construction activity 2 $[Id_{A2p}]$ is:

$$[Id_{A2p}] = [1.11 \quad 1.17 \quad 1.03 \quad 1.05]$$

For construction activity 2, the corresponding produced output for construction family A (see matrix $[Po]$) is:

$$[Po_{A2p}] = [6.00 \quad 8.00 \quad 6.50 \quad 7.00]$$

then

$$Cid = \frac{6 \times 1.11 + 8 \times 1.17 + 6.5 \times 1.03 + 7 \times 1.05}{6 + 8 + 6.5 + 7} = 1.09$$

Example 4. Subfamily of Construction Parts, from a Family, with the Greatest Effect of Design on a Given Construction Activity

Let consider two subfamilies of construction parts in family A:

- Subfamily A1 is composed of the construction parts 1 and 2
- Subfamily A2 is composed of the construction parts 3 and 4

Then for construction activity 2 and family A, $[Id_{A2p}]$ and $[Po_{A2p}]$ (see Example 3) can be expressed as:

$$[Id_{A2p}] = [[1.11 \quad 1.17] \quad [1.03 \quad 1.05]]$$

$$[Po_{A2p}] = [[6.00 \quad 8.00] \quad [6.50 \quad 7.00]]$$

For subfamily A1 the cumulative index of difficulty (see Equation 10) is:

$$Cid = \frac{6 \times 1.11 + 8 \times 1.17}{6 + 8} = 1.14$$

For subfamily A2 the cumulative index of difficulty (see Equation 10) is:

$$Cid = \frac{6.5 \times 1.03 + 7 \times 1.05}{6.5 + 7} = 1.04$$

The cumulative indexes of the subfamilies can be arranged on a row matrix $[Cid_{A2p}]$.

$$[Cid_{A2p}] = [1.14 \quad 1.04]$$

In Family A, the construction parts of subfamily A1 (cumulative index of difficulty 1.14) are the ones whose design has the greatest effect on construction activity 2.

Example 5. Construction Activity Most Affected by the Design of a Given Construction Part

Consider the indexes of difficulty of construction parts 2 for their required construction activities (the second column of $[Id]$), see example 1).

$$[Id_{c2}] = \begin{bmatrix} 0.00 \\ 1.17 \\ 1.08 \\ 1.04 \end{bmatrix}$$

From there, the indexes of difficulty of construction parts 2 for their really required construction activities can be arranged on a column matrix $[Id_{P2a}]$.

$$[Id_{P2a}] = \begin{bmatrix} 1.17 \\ 1.08 \\ 1.04 \end{bmatrix}$$

For construction part 2, the activity 2 in $[Id_{c2}]$ (index of difficulty 1.17) is the most affected by the design of this construction part.

Example 6. Construction Activity Most Affected by the Design of a Given Subfamily of Construction Parts

Using Equation 10, the cumulative index for subfamily A1 can be calculated for each construction activity and then arranged in a column matrix $[Cid_{P\,A}]$.

$$[Id_{Pa}] = \begin{bmatrix} 1.11 & 1.17 \\ 1.08 & 1.08 \\ 1.05 & 1.04 \end{bmatrix} \rightarrow \quad [Cid_{P\,A}] = \begin{bmatrix} 1.144 \\ 1.080 \\ 1.043 \end{bmatrix}$$

For subfamily A1 of construction parts, the activity with the highest cumulative index (Cid = 1.144) is the most affected by the design of these construction parts.

Example 7. Effect of the Design of a Construction Part on Construction Work

The effect of the design of construction part 2 on construction work can be determined with the index of difficulty of the construction part 2 (Equation 16).

$$IdC = \frac{RPo_B}{RPo} \times \frac{\sum_{i\in\{A\}} Elur_{Bi} \times Po_i \times Id_i}{\sum_{i\in\{A\}} Elur_{Bi} \times Po_{B\,i}}$$

From Example 5 the indexes of difficulty of construction part 2 for their required construction activities are:

$$[Id_{c2}] = \begin{bmatrix} 0.00 \\ 1.17 \\ 1.08 \\ 1.04 \end{bmatrix}$$

The corresponding produced outputs for their construction activities (see matrix $[Po]$) are:

$$[Po_{c2}] = \begin{bmatrix} 0.00 \\ 8.00 \\ 3.25 \\ 0.65 \end{bmatrix}$$

For construction part 2 and their required construction activities, $[Po_{B\,c2}]$ and $[Elur_{B\,c2}]$ can be obtained from matrices $[Po_B]$ and $[Elur_B]$. These are:

$$[Po_{B\,c2}] = \begin{bmatrix} 0.00 \\ 5.00 \\ 2.40 \\ 0.40 \end{bmatrix}$$

$$[Elur_{B\,c2}] = \begin{bmatrix} 0.00 \\ 1.50 \\ 2.00 \\ 4.00 \end{bmatrix}$$

Taking as representative output, the produced output of activity 3, then $RPo_B = 2.40$ and $RPo = 3.25$.

$$IdC = \frac{2.40}{3.25} \times \frac{1.50 \times 8.00 \times 1.17 + 2.00 \times 3.25 \times 1.08 + 4.00 \times 0.65 \times 1.04}{1.50 \times 5.00 + 2.00 \times 2.40 + 4.00 \times 0.40} = 1.26$$

Example 8. Construction Part, from a Family, with the Greatest Effect of Design on Construction Work

The indexes of difficulty for each construction part of family A can be calculated using Equation 16 (see Example 7) and then arranged in a row matrix $[IdC_P]$.

$$[IdC_P] = [1.07 \quad 1.26 \quad 1.18 \quad 1.19]$$

In Family A, the construction part 2 (index of difficulty of the construction part 1.26) is the one whose design has the greatest effect on construction work.

Example 9. Effect of the Design of a Family of Construction Parts on Construction Work

The effect of the design of construction parts family A on construction work can be determined with the cumulative index of difficulty of construction parts $CidC$ (Equation 22).

$$CidC = \frac{\sum_{j \in \{P\}} RPo_j \times IdC_j}{\sum_{j \in \{P\}} RPo_j}$$

As was established in Example 8, the row matrix of indexes of difficulty of construction parts of family A $[IdC_P]$ is:

$$[IdC_P] = [1.07 \quad 1.26 \quad 1.18 \quad 1.19]$$

Taking as representative output, the produced output of activity 3, then for the construction parts of A family, the representative output $[RPo]$ (see matrix $[Po]$) is:

$$[RPo] = [3.00 \quad 3.25 \quad 2.75 \quad 3.00]$$

then

$$CidC = \frac{3.00 \times 1.07 + 3.25 \times 1.26 + 2.75 \times 1.18 + 3.00 \times 1.19}{3.00 + 3.25 + 2.75 + 3.00} = 1.18$$

Example 10. Subfamily of Construction Parts, from a Family, With the Greatest Effect on Construction Work

For family A, $[IdC_P]$ and $[RPo]$ (see Example 9) can be expressed as

$$[IdC_P] = [[1.07 \quad 1.26] \quad [1.18 \quad 1.19]]$$

$$[RPo] = [[3.00 \quad 3.25] \quad [2.75 \quad 3.00]]$$

Using Equation 22, the cumulative index of difficulty of construction parts can be calculated for:

Subfamily A1

$$CidC = \frac{3.00 \times 1.07 + 3.25 \times 1.26}{3.00 + 3.25} = 1.17$$

And for subfamily A2

$$CidC = \frac{2.75 \times 1.18 + 3.00 \times 1.19}{2.75 + 3.00} = 1.18$$

Then these cumulative indexes of difficulty of construction parts can be arranged in a row matrix $[CidC_P]$.

$$[CidC_P] = [1.17 \quad 1.18]$$

In Family A, the construction parts of subfamily A2 (cumulative index of difficulty of construction part 1.18) are the ones whose design has the greatest effect on construction activity 2.

CHAPTER 6

EXTENDING THE USE OF THE INDEX OF DIFFICULTY

6.1 Considerations About Crews and Means and Methods on the Effect of Building Design on Construction Work

Crews

As stated, the index of difficulty evaluates in relative terms how much the design features of a construction part affect the work required by this construction part.

This measure is obtained by comparing the average effective work effort per unit of produced output spent by a crew in doing a work for two design conditions. So, by definition, the index of difficulty of a construction part for a required construction activity is calculated for a given crew.

For a given construction part and a given construction activity, let us consider two crews A and B, then the indexes of difficulty associated with each crew will be Id_A and Id_B. The relation Id_A/Id_B does not provide a relative measure of the effect of design on the work of each crew. That is because, although the design is the same, the basis of comparison also depends on the crew's skills ($Elur_B$ is not the same).

For the proper evaluation of the effect of a given design on the work of two crews, a relative index of difficulty can be used. This index, the relative index of difficulty for crew A with respect to crew B (Rid_c), is the ratio between the average effective work effort per unit of produced output spent by crew A, and the average effective work effort per unit of produced output spent by crew B, both crews working in the same construction activity for the same construction part. Under these conditions, the produced output (Po) is also the same. Then by definition:

$$Rid_c = \frac{\frac{Atpt_A}{Po}}{\frac{Atpt_B}{Po}} = \frac{Atpt_A}{Atpt_B} \tag{23}$$

Where:

$Atplt_A$ is the average total productive labor time spent by crew A in the construction activity for the construction part

$Atplt_B$ is the average total productive labor time spent by crew B in the construction activity for the construction part

From (8)

$$Atpt_A = Elur_{B\ A} \times Po \times Id_A \tag{24}$$

$$Atpt_B = Elur_{B\ B} \times Po \times Id_B \tag{25}$$

Where:

$Elur_{B\ A}$ is the effective labor unit rate of the required activity for crew A working in the construction part with base design

$Elur_{B\ B}$ is the effective labor unit rate of the required activity for crew B working in the construction part with base design

Replacing (24) and (25) in (23)

$$Rid_c = \frac{Elur_{B\ A} \times Po \times Id_A}{Elur_{B\ B} \times Po \times Id_B}$$

Finally

$$Rid_c = \frac{Elur_{B\ A}}{Elur_{B\ B}} \times \frac{Id_A}{Id_B} \tag{26}$$

Let consider for instance Id_A = 1.2, $Elur_{\ B\ A}$ =2.0, Id_B= 1.3, and $Elur_{B\ B}$ =1.5

then:

$$Rid_c = \frac{2}{1.5} \times \frac{1.2}{1.3} = 1.23$$

The effect of the current design on crew A is 1.23 times the effect on crew B. Crew B is more qualified, spends less work effort to complete the work.

Groups of crews

It was stated that the index of difficulty can also be calculated for a group of crews. In this case, the effective labor unit rate can be calculated as the average of the effective labor unit rate corresponding to the crews.

If n is the number of crews and $\{C\}$ is the set of subindices that define the crews, then the effective labor unit rate corresponding to the base design ($Elur_B$) is:

$$Elur_B = \frac{\sum_{i\in\{C\}} Elur_{Bi}}{n} \tag{27}$$

And the effective labor unit rate corresponding to a given design ($Elur$) is:

$$Elur = \frac{\sum_{i\in\{C\}} Elur_i}{n} \tag{28}$$

The index of difficulty (Id_i)corresponding to the crew i is:

$$Id_i = \frac{Elur_i}{Elur_{Bi}}$$

Then

$$Elur_i = Id_i \times Elur_{Bi} = Elur_{Bi} \times Id_i \tag{29}$$

Replacing (29) in (28)

$$Elur = \frac{\sum_{i\in\{C\}} Elur_{Bi} \times Id_i}{n} \tag{30}$$

Replacing (27) and (30) in the definition of Id

$$Id = \frac{\frac{\sum_{i\in\{C\}} Elur_{Bi} \times Id_i}{n}}{\frac{\sum_{i\in\{C\}} Elur_{Bi}}{n}}$$

Finally

$$Id = \frac{\sum_{i\in\{C\}} Elur_{Bi} \times Id_i}{\sum_{i\in\{C\}} Elur_{Bi}} \tag{31}$$

The index of difficulty (Id) for a group of construction crews is equal to the weighted average of the indexes of difficulty for each crew. Weights are the effective labor unit rate for each crew for a construction part with the base design.

For the data in the example, the index of difficulty for this group of construction crews is:

$$Id = \frac{2.0 \times 1.20 + 1.5 \times 1.30}{2.00 + 1.5} = 1.24$$

One major possibility to extend the use of the index of difficulty is related to the development of standard models for average productive time spent in construction tasks as a function of the quantity of work to be done. In the case of a linear relation, for instance, this will lead to the definition of standard productive time per unit of work of construction tasks. The standards could represent an agreement on the expected performance in the sector. Once defined, the evaluation of the effect of design will be on the work of a representative crew, so on ahead the calculations will depend on these standards.

It should be noted that similar standards at construction activity level have been developed in many countries. In the former Eastern European countries, once part of the USSR, a centralized state regulation of price formation in construction was employed. A "quotation norm" serves as a technical and economic specification related to construction processes, encompassing the standardized resource consumption (materials, labor, equipment) required for a specific unit of work. In Russia, efforts to streamline construction production began in 1811 leading to the development of labor, machinery, and materials consumption norms. In subsequent years, this regulatory framework underwent revisions, with significant changes occurring during the Soviet era in 1955-56, establishing the normative basis for state estimates and construction price formation. Other eastern European countries adopted the same consideration, in Romania for instance, the first indicators of quotation norms with a general and mandatory character of application appeared at the end of the 1950s. (Vascan, 2021). In Turkey, the unit price system of the Ministry of Public Works, used in preparing tender documents and in planning production, publish every year man-day values for many construction activities (Akcali, 2013, cited in Ulubeyli et al., 2014). For several countries in Africa and Asia, the International Labour Organisation's (ILO) program, Advisory Support Information Services and Training (ASIST), make a synthesis of prevailing productivity norms for road construction and maintenance activities (Stiedl et al., 1998). In Netherlands, the Dutch Association of Cost Engineers, (DACE) has issued the Dace Labour Norms. The document offers standard times for numerous activities in industrial construction (Van Vliet, 2011).

In the United States, the RSMeans Building Construction Cost is widely used for estimating construction costs. It contains, along with a wide range of other information, the amount of labor required to perform one unit of work. The NECA Manual of Labor Units is a manual that provides labor units (a standardized measure of labor time required to complete a specific task or activity, often expressed in hours or minutes) for different activities in the electrical construction field.

The extended practice of using standard unit labor at the construction activity level for estimation purposes suggests that developing standard unit labor at the construction task level could enhance the feasibility of using the index of difficulty.

Means and Methods

To evaluate the effect of design, the index of difficulty for a given construction activity is calculated considering that this is carried out with the same means and methods. However, different means and methods can be employed in a construction activity. Given a construction part, the effect of its design on a construction activity carried out with different means and methods can be evaluated using a relative index of difficulty. Means and methods with lesser difficulty can be considered more efficient.

For a given construction part and a given construction activity, let's consider two means and methods A and B, then its associated indexes of difficulty will be Id_{mA} and Id_{mB}. The relative index of difficulty for a means and method A with respect to a means and method B (Rid_m), is the ratio between the average effective work effort per unit of produced output spent working with means and methods A and the average effective work effort per unit of produced output spent working with means and methods B. As the construction part and the construction activity are the same, the produced output (Po) is too. Then by definition:

$$Rid_m = \frac{\frac{Atpt_{mA}}{Po}}{\frac{Atpt_{mB}}{Po}} = \frac{Atpt_{mA}}{Atpt_{mB}} \tag{32}$$

Where:

$Atplt_{mA}$ is the average total productive labor time spent in the construction activity with means and methods A for the construction part

$Atplt_{mB}$ is the average total productive labor time spent in the construction activity with means and methods B for the construction part

From (8)

$$Atpt_{mA} = Elur_{B\ mA} \times Po \times Id_{mA} \quad (33)$$

$$Atpt_{mB} = Elur_{B\ mB} \times Po \times Id_{mB} \quad (34)$$

Where:

$Elur_{B\ mA}$ is the effective labor unit rate of the activity with means and method A working in the construction part with base design

$Elur_{B\ mB}$ is the effective labor unit rate of the activity with means and method B working in the construction part with base design

Replacing (33) and (34) in (32)

$$Rid_m = \frac{Elur_{B\ mA} \times Po \times Id_{mA}}{Elur_{B\ mB} \times Po \times Id_{mB}}$$

Finally

$$Rid_m = \frac{Elur_{B\ mA}}{Elur_{B\ mB}} \times \frac{Id_{mA}}{Id_{mB}} \quad (35)$$

Let consider for instance Id_{mA} = 1.25, $Elur_{B\ mA}$ =2.0, Id_{mB}= 1.10, and $Elur_{B\ mB}$ =1.8 then:

$$Rid_m = \frac{2.0}{1.8} \times \frac{1.25}{1.10} = 1.26$$

For the given design, means and method A required more work effort than means and method B, hence this latter will be more efficient than the first.

6.2 Comparing the Effect of Different Designs at Solution Level

On occasions, it can be of interest to compare the effect of the design of different construction parts but with the same functions on its required construction work. That is, to compare the average work effort required to build two different construction part solutions for the same functions. For instance, for floor finishing compare the effect of design of a floor tiling solution with a carpet solution on the required construction work. The means of measuring this effect for two situations are presented below.

Comparing the Effect of the Design of two Families of Construction Parts with the Same Function on Construction Work

To solve any design requirements many solutions can be proposed. In general, two families of construction parts that accomplish the same function do not need to be composed of the same group of construction parts. In this situation, it can be of interest to compare the effect of the design of these two families of construction parts on its construction work. As these construction part families are solutions to a requirement, the comparison of the effect must be done in absolute terms, that is, the effect of design is related to the average work effort required to build the family of construction parts.

Let's consider two families of construction parts A and B. Again, a relative index of difficulty can be used to measure the effect of the design solutions on its construction work. This index, the relative index of difficulty for family A with respect to family B (Rid_f), is the ratio between the average effective work effort spent working to build the family A of construction parts ($Aewe_{FA}$) and the average effective work effort spent working to build the family B of construction parts ($Aewe_{FA}$). Then by definition:

$$Rid_f = \frac{Aewe_{FA}}{Aewe_{FB}} \quad (36)$$

For family A

$$Aewe_{fA} = \sum_{j \in \{F_A P\}} \sum_{i \in \{F_A A\}} Atplt_{i\,j} \quad (37)$$

Where:

$Atplt_{i\,j}$ is the average total productive labor time required to carry out the activity *i* of the construction part j with a given design

$\{F_A A\}$, is the set of subindices that define the construction activities really required by the family A and $\{F_A P\}$ is the set of subindices that define the construction parts from the family A.

From (8)

$$Atplt_{ij} = Elur_{Bi} \times Po_{ij} \times Id_{ij} \quad (38)$$

Where:

$Elur_{Bi}$ is the effective labor unit rate of the required activity i for construction part *j* with base design

Po_{ij} is the produced output of the required activity i for the construction part *j* with a given design

Id_{ij} is the index of difficulty of the construction part *j* for the required activity *i*

Replacing (38) for family A in (37)

$$Aewe_{FA} = \sum_{j \in \{F_A P\}} \sum_{i \in \{F_A A\}} Elur_{Bi} \times Po_{ij} \times Id_{ij} \quad (39)$$

Swapping summations

$$Aewe_{FA} = \sum_{i \in \{F_A A\}} \sum_{j \in \{F_A P\}} Elur_{Bi} \times Po_{ij} \times Id_{ij}$$

Given that $Elur_{Bi}$ of a construction activity *i* is the same for all construction parts, then:

$$Aewe_{FA} = \sum_{i \in \{F_A A\}} Elur_{Bi} \sum_{j \in \{F_A P\}} Po_{ij} \times Id_{ij} \quad (40)$$

From (10) and (11); and for family A

$$\sum_{j \in \{F_A P\}} Po_{ij} \times Id_{ij} = Cpo_i \times Cid_i \quad (41)$$

Where:

Cpo_i is the cumulative produced output of the required activity i for a family of construction parts

Cid_i is the cumulative index of difficulty of a family of construction parts for a construction activity *i*

Replacing (41) in (40)

$$Aewe_{FA} = \sum_{i \in \{F_A A\}} Elur_{Bi} \times Cpo_i \times Cid_i \quad (42)$$

Replacing (42) in (36) and doing the same for family B

$$Rid_f = \frac{\sum_{i \in \{F_A A\}} Elur_{Bi} \times CPo_i \times Cid_i}{\sum_{i \in \{F_B A\}} Elur_{Bi} \times CPo_i \times Cid_i} \quad (43)$$

This expression for Rid_f can be used to compare the effect of the design of these two families of construction parts on its construction work.

Although the previous development corresponds to a more general case when both sets of construction parts are different but with the same function, it can be also applied, as a particular case, when both sets of construction parts are similar.

Comparing the Effect of Design of two Groups of Families of Construction Parts with the Same Function

This is a more general situation than the previous case. The interest here is comparing the effect of the design of two groups of families of construction parts on its construction work. The design of these groups of families is considered a design solution.

The comparison can be made following the same consideration that the previous case, only changing the scope, from a family to a group of families. A relative index of difficulty would also be used for this purpose.

Consider the families groups of construction parts A and B. The relative index of difficulty for a group of families A with respect to a group of families B (Rid_g), is the ratio between the average effective work effort spent working to build the group of families A ($Aewe_{GA}$) and the average effective work effort spent working to build the group of families B ($Aewe_{GB}$). Then by definition:

$$Rid_g = \frac{Aewe_{GA}}{Aewe_{GB}} \quad (44)$$

For family A

$$Aewe_{GA} = \sum_{k \in \{G_A F\}} Aewe_{Fk} \quad (45)$$

$\{G_A F\}$ is the set of subindices that define the group of families A

Replacing (45) in (44), and doing the same for the group of families B

$$Rid_g = \frac{\sum_{k \in \{G_A F\}} Aewe_{Fk}}{\sum_{k \in \{G_B F\}} Aewe_{Fk}} \quad (46)$$

Replacing (42) in (45) for families in groups A and B

$$Rid_g = \frac{\sum_{k\in\{G_AF\}} \sum_{i\in\{G_AF_kA\}} Elur_{B\ i\ k} \times CPo_{i\ k} \times Cid_{i\ k}}{\sum_{k\in\{G_BF\}} \sum_{i\in\{G_BF_kA\}} Elur_{B\ i\ k} \times CPo_{i\ k} \times Cid_{i\ k}} \quad (47)$$

Where:

$Elur_{B\ i\ k}$ is the effective labor unit rate of a required activity i for a construction part, from a family k, with base design

$Cpo_{i\ k}$ is the cumulative produced output of a required activity i for a family of construction parts k

$Cid_{i\ k}$ is the cumulative index of difficulty of a family of construction parts k for the construction activity *i* with a given design

$\{G_AF_kA\}$,$\{G_BF_kA\}$ are the set of subindices that define the construction activities really required by the family k of the group A and B respectively, and $\{G_AF\}$, $\{G_BF\}$ are the set of subindices that define the group of families A and B respectively.

Any other scenario that required a comparison of the effect of design on construction work can be made by drawing on the concept of the relative index of difficulty. This index compares the average effective work effort spent on construction work under two conditions.

CHAPTER 7

APLICATION CASES

7.1 Application Case A. Index of Difficulty and Cumulative Index of Difficulty

Figure 2 shows the floor plan of the second floor of the eastern block of the Civil Engineering Department building at the University of Piura -henceforth the CE building-. The building was selected to serve as a case of application of the index of difficulty and the cumulative index of difficulty for floor tiling. For this construction activity, floor finishing of office rooms 1, 2, 3, and the corridor are considered the construction parts (see areas and perimeters in Figure 2).

Figure 2

Second Floor of the Eastern Block of the Civil Engineering Department Building at the University of Piura

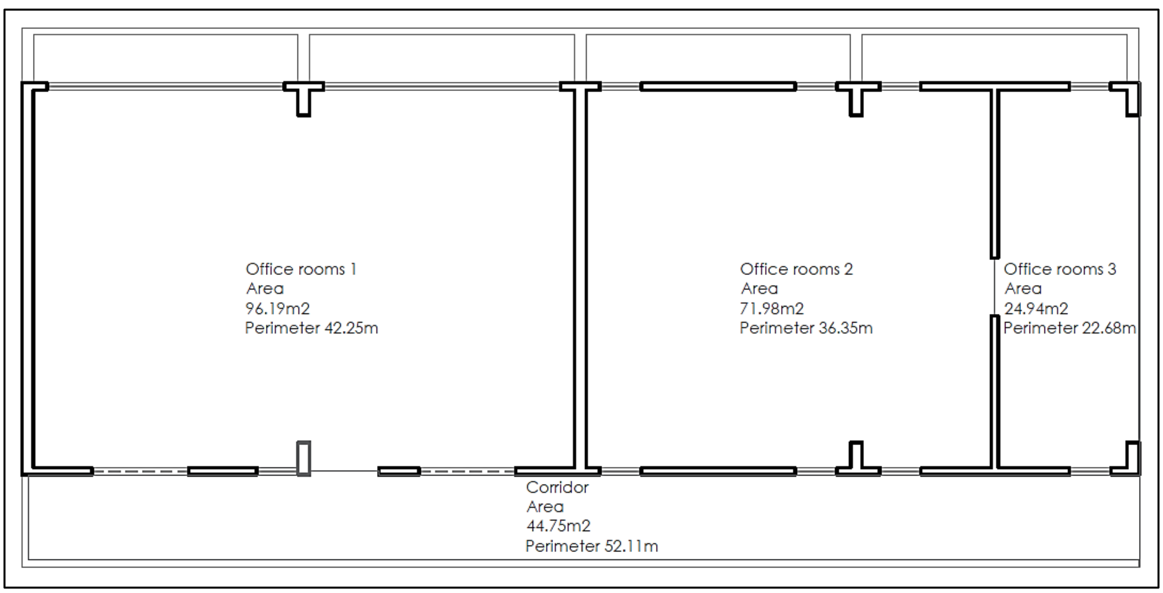
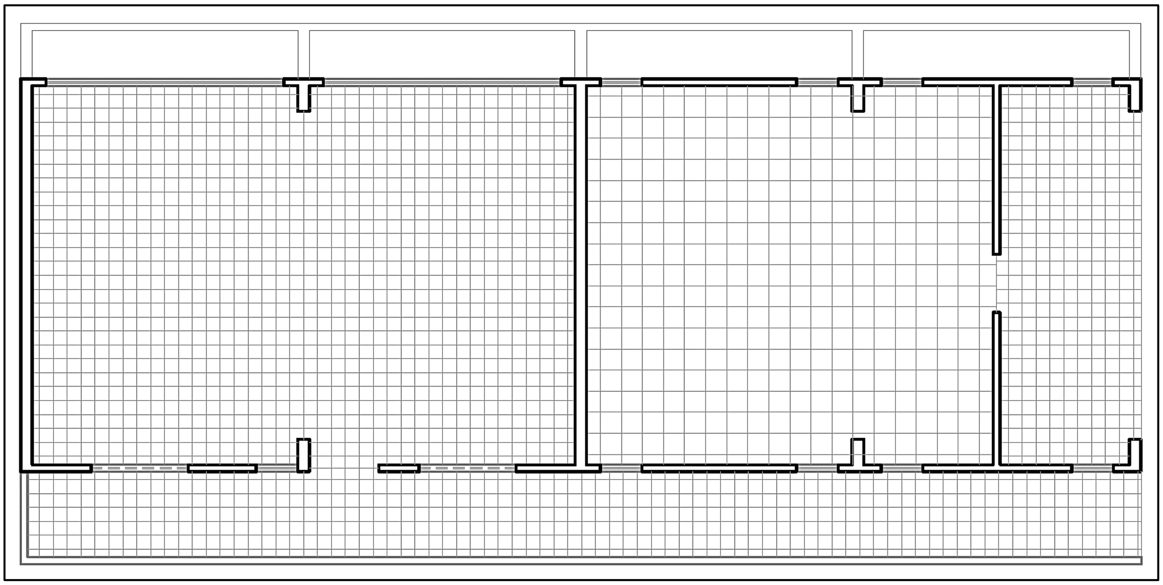


Figure 3 shows the current tile design on the CE building. The floor is covered with square tiles of 30 cm. and 45 cm.

Figure 3

Current Tile Flooring Design of the Second Floor of the Eastern Block of the Civil Engineering Department Building at the University of Piura



The base design is a floor finish with 30x30 cm tiles placed on a square-shaped region 4 meters on each side, as shown in Figure 4.

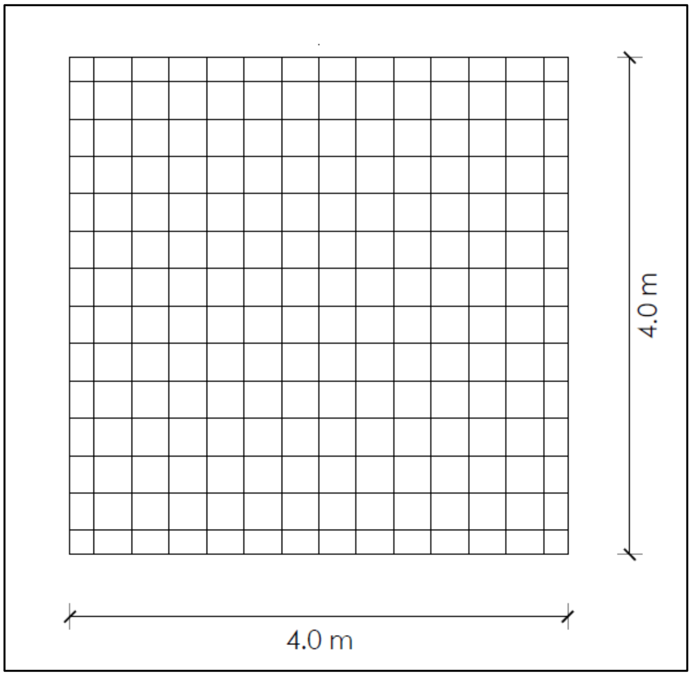
Construction Tasks Required by Floor Tiling

Tasks for floor tiling were identified from the recorded videos of the work carried out by a crew on the floor tiling activity. The tasks were classified into those required for cutting and those required for installation.

Handling tiles, measuring cuts, marking tiles, setting tiles, cutting tiles, and storing tiles are the tasks required for cutting. Installing requires preparing adhesive, spreading adhesive, handling tiles, positioning tiles, and setting and leveling tiles.

Figure 4

Floor Finishing Base Design for Floor Tiling



Relationship Between the Average Productive Time Spent on a Task and the Quantity of Work to be Done

Table 2 displays the average productive times per unit of work of the tasks required for floor tiling. They were estimated based on measurements obtained from recorded videos of floor tiling activity. A linear relationship was identified between the average productive time of tasks and the amount of work to be done.

Quantities of Work to Be Done on Tasks

In order to determine the average productive time needed for each task, it is necessary to calculate the respective quantities of uncut tiles, tiles with one cut, tiles with two cuts, and tiles with three cuts, as well as the length of each cut and the area of the construction part. Figure 5 shows this data for the base design.

Table 2

Average Productive Times per Unit of Work of Floor Tiling Tasks

Task	Average productive time per unit		Observations
I Cutting			
Handling tiles	20	sec/piece	
Measuring tiles *	10	sec/point	
Marking tiles	0.2	sec/cm	
Setting tiles	4	sec/piece	
Cutting tiles	1	sec/cm	
Storing tiles	10	sec/piece	
II Installing			
Preparing adhesive	90	sec/m2	
Spreading adhesive	300	sec/m2	
Handling tiles	10	sec/piece	
Positioning tiles	5	sec/piece	for cut tiles
Setting & leveling tiles	55	sec/piece	for 30x30 pieces
	110	sec/piece	For 45x45 pieces

* Point refers to the number of measures to be taken. For tiles with one cut, point is equal to 2; for tiles with two cuts, point is equal to 4; and for tiles with three cuts, point is equal to 6.

Figure 5

Tile Floor Quantities for Base Design

Base design	30x30 cm	Area =	16	m2
Total tiles	196			
Uncut tiles	144			
Cut tiles	52			

One cut	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	24	19.5	x	30.0	30.0	720
	24	30.0	x	19.5	30.0	720
	48					1440

Two cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	4	22.0	x	17.0	39.0	156
	4					156
					Total cutting length (cm)	1596

Tile floor quantities for all construction parts are shown in Appendix A. Data for offices rooms 1 is shown in Figure 6. In both cases, this data was extracted from digital drawings using the functionalities provided by computer-aided design software**.**

Figure 6

Tile Floor Quantities for Office Rooms 1

Office rooms 1	30x30 cm		Area =	96.19	m2
Total tiles	1120				
Uncut tiles	980				
Cut tiles	140				

One cut	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	67	18.5	x	30.0	30.0	2010
	52	30.0	x	15.5	30.0	1560
	4	30.0	x	17.5	30.0	120
	4	26.0	x	30.0	30.0	120
	127					3810
Two cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	4	18.5	x	15.5	34.0	136
	3	18.5	x	17.5	36.0	108
	1	26.0	x	17.5	43.5	44
	4	-6.5	x	-12.5	19.0	76
	12					364
Three cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	1	26.0				
		18.5	x	12.0	41.5	42
	1					42
					Total cutting length (cm)	4215

Average Total Productive Labor Time Spent in Floor Tiling

With previous data, the average productive time required for floor tiling can be determined (see Appendix C). This is done by adding the productive time of all required tasks. The productive time of a task is a function of the amount of work to be done, for example (see Figure 7) cutting tiles in room offices 1 requires 3810 cm of cutting length for tiles with one cut, 363.5 cm for tile with two cuts tiles, and 41.5 cm. for tiles with three cuts.

Figure 7

Calculation of the Average Total Productive Labor Time Required by Floor Tiling for Office Rooms 1

Office rooms 1	
Tile dimension	30x30
Area	96.19 m2

Tile pieces information

Tile information		**Uncut tiles**	**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Totals**
Number of pieces		980	127	12	1	1120
Cut length (cm)			3810	364	42	4215

Productive time for cutting tiles

Task	**Average productivity time per unit**		**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Productive time (hour)**
Handling tiles	20 sec/piece		2540	240	20	0.78
Measuring tiles	10 sec/point		2540	480	60	0.86
Marking tiles	0.2 sec/cm		762	73	8.3	0.23
Setting tiles	4 sec/piece		508	48	4	0.16
Cutting tiles	1 sec/cm		3810	363.5	41.5	1.17
Storing tiles	10 sec/piece		1270	120	10	0.39
						3.58

Productive time for installing tiles

Task	**Average productivity time per unit**	**Uncut tiles**	**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Productive time (hour)**
Preparing adhesive	120 sec/m2					3.21
Spreading adhesive	300 sec/m2					8.02
Handling tiles	20 sec/piece	19600	2540	240	20	6.22
Positioning tiles	5 sec/piece		635	60	5	0.19
Setting tiles	55 sec/piece	53900	4547	398	42	16.36
						34.00
Average total productive labor time = 3.58 + 34.00 = 37.58 labor hours						37.58

Given that for cutting tiles the average productive time per length of cut is 1 sec/cm, the average productive time for this task is:

$$1\ \frac{\text{sec}}{\text{cm}} \times (3810 + 363.5 + 41.5)\text{cm} \times \frac{1}{3600}\ \frac{\text{hour}}{\text{sec}} = 1.17\ \text{hour}$$

Similar calculations have been made for all tasks required by floor tiling. Figure 7 shows the data and partial results of these calculations. The average total productive labor time ($Atplt$) for floor tiling of office rooms 1 is 37.58 labor-hours.

Figure 8 shows the data and partial results for calculations of the average total productive labor time for floor tiling with base design (7.11 labor hour).

Figure 8

Calculation of the Average Total Productive Labor Time Required by Floor Tiling for Base Design

Base design
Tile dimension 30x30
Area 16 m2

Tile pieces information

Tile information		Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Totals
Number of pieces		144	48	4		196
Cut length (cm)			1440	155		1595

Productive time for cutting tiles

Task	Average productivity time per unit	One cut tiles	Two cuts tiles	Three cuts tiles	Productive time (hour)
Handling tiles	20 sec/piece	960	80	0	0.29
Measuring tiles	10 sec/point	960	160	0	0.31
Marking tiles	0.2 sec/cm	288	31	0	0.09
Setting tiles	4 sec/piece	192	16	0	0.06
Cutting tiles	1 sec/cm	1440	155	0	0.44
Storing tiles	10 sec/piece	480	40	0	0.14
					1.33

Productive time for installing tiles

Task	Average productivity time per unit	Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Productive time (hour)
Preparing adhesive	120 sec/m2					0.53
Spreading adhesive	300 sec/m2					1.33
Handling tiles	20 sec/piece	2880	960	80	0	1.09
Positioning tiles	5 sec/piece		240	20	0	0.07
Setting tiles	55 sec/piece	7920	1876	110	0	2.75
						5.78

Average total productive labor time = 1.33 + 5.78 = 7.11 labor hours 7.11

Effective Labor Unit Rate

To calculate the effective labor unit rate, the average total productive labor time spent in the execution of tasks must be divided by the amount of produced output (Po).

For office rooms 1, $Atplt$ = 37.58 labor -hours and Po =96.19 m^2, then

$$Elur = \frac{37.58 \text{ labor} - \text{hours}}{96.19\text{m}^2} = 0.391 \text{ labor} - \text{hours/m}^2$$

For base design, $Atplt$ = 7.11 labor -hours and Po =16.0 m^2, then

$$Elur_B = \frac{7.11 \text{ labor} - \text{hours}}{16.0\text{m}^2} = 0.444 \text{ labor} - \text{hours/m}^2$$

This latter value is used for the calculation of the index of difficulty of all the construction parts.

Index of Difficulty

By definition, the index of difficulty of floor finish of office rooms 1 for floor tiling is calculated as:

$$Id = \frac{Elur}{Elur_B} = \frac{0.391 \text{ labor} - \text{hours}}{0.444 \text{ labor} - \text{hours}} = 0.88$$

The average work effort per unit of output spent in floor tiling for office rooms is 0.88 times the average work effort per unit of output spent in floor tiling for the base design. Hence, the effect of the design features of office rooms 1 on tile flooring is 0.88 times the effect of the base design features on this activity. That means that for floor tiling, the index of difficulty of the office rooms 1 is 0.88. There is a direct correspondence between the design features effect and the difficulty to perform a construction activity.

Following the same procedure, the index of difficulty has been calculated for all construction parts. These values and the data needed for calculation are shown in Table 3.

From Table 3, one can observe that the effective labor unit rate, *Elur*, is not constant although the average productive time per unit of work for each task required by floor tiling is constant. The values would show that for floor tiling, the size and shape of the room and the size of the tile affect the effective labor unit rate.

Table 3

Index of Difficulties of Construction Parts for Floor Tiling and Data for its Calculations

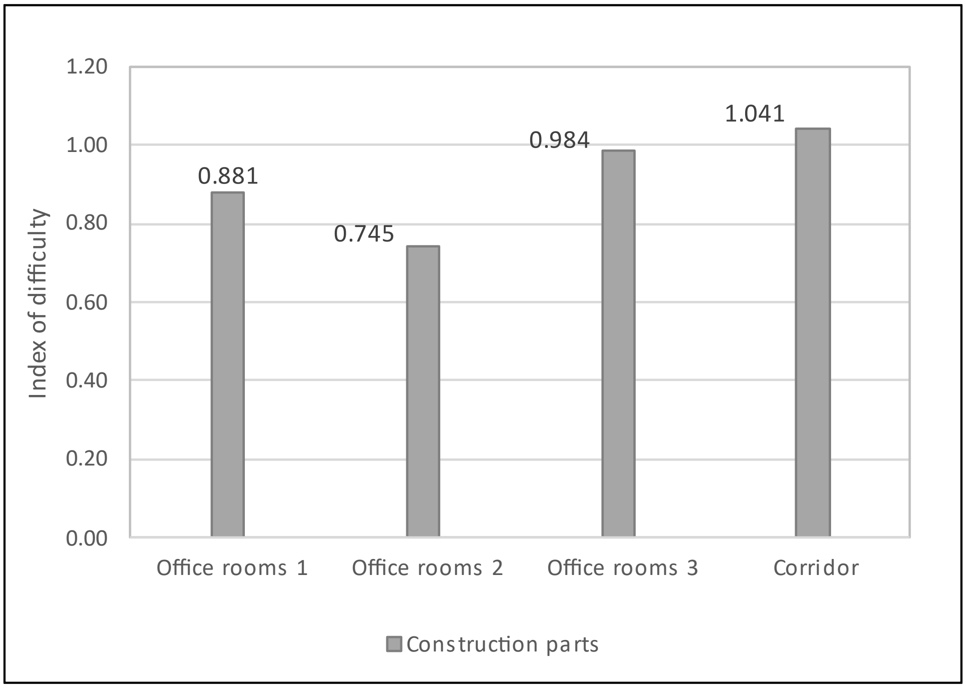
Construction part	Office rooms 1	Office rooms 2	Office rooms 3	Corridor
Po (m2)	96.19	71.98	24.94	44.75
$Atplt$ (labor -hour)	37.58	23.81	10.90	20.68
$Elur$ (labor-hour/m2)	0.391	0.331	0.437	0.462
Id	0.881	0.745	0.984	1.041

Note. The index of difficulty has been calculated for $Elur_B$ = 0.444 labor hours/m^2

Given a construction activity, the work of a crew progresses during the project construction. This progress can be measured in terms of the construction parts where the work is carried out. Consider that the crew works on floor tiling following the sequence office rooms 1, office rooms 2, office rooms 3, and corridor. The associated index of difficulty of each construction part allows determining how the difficulty to carry out the construction activity changes as work progresses. This variation can be represented in a graphic (see Figure 9) to show how the average work effort spent by a crew change during the construction of a project as a consequence of changes in the design features of the construction parts.

Figure 9

Progress of the Index of Difficulty for Floor Tiling of 2nd Floor of CE Building



The values of the index of difficulty of the construction parts must be compared for determining the one whose design has the greatest effect on the floor tiling (demands more average work effort per unit of produced output). This is the one with the highest index, in our case, the floor finishing of the corridor (*Id* = 1.041).

Cumulative Index of Difficulty of a family

Figure 10 shows the calculation of the cumulative index of difficulty for a progressive aggregation of the construction parts. Equation 10 is used for this purpose.

For example, for the subfamily that is composed of the office rooms, the cumulative index of difficulty is:

$$Cid = \frac{96.19 \times 0.881 + 71.98 \times 0.745 + 24.94 \times 0.984}{96.19 + 71.98 + 24.94} = 0.84$$

So, the effect of the design features of all office rooms is 0.84 times the effect of the base design features on this activity. That means that for floor tiling, the index of difficulty of all office rooms is 0.84.

Figure 10

Cumulative Indexes of Difficulty for Floor Tiling

Office rooms 1, and Office rooms 2

Construction part	Po (m2)	Id	Po x Id (m2)
Office rooms 1	96.19	0.881	84.743
Office rooms 2	71.98	0.745	53.625
Totals	168.17		138.368
		***Cid* =**	**0.823**

Office rooms 1, Office rooms 2, and Office rooms 3

Construction part	Po (m2)	Id	Po x Id (m2)
Office rooms 1	96.19	0.881	84.743
Office rooms 2	71.98	0.745	53.625
Office rooms 3	24.94	0.984	24.541
Totals	193.11		162.909
		***Cid* =**	**0.844**

Office rooms 1, Office rooms 2, Office rooms 3, and Corridor

Construction part	Po (m2)	Id	Po x Id (m2)
Office rooms 1	96.19	0.881	84.743
Office rooms 2	71.98	0.745	53.625
Office rooms 3	24.94	0.984	24.541
Corridor	44.75	1.041	46.585
Totals	237.86		209.494
		***Cid* =**	**0.881**

7.2 Application Case B. Index of Difficulty and Crew Considerations

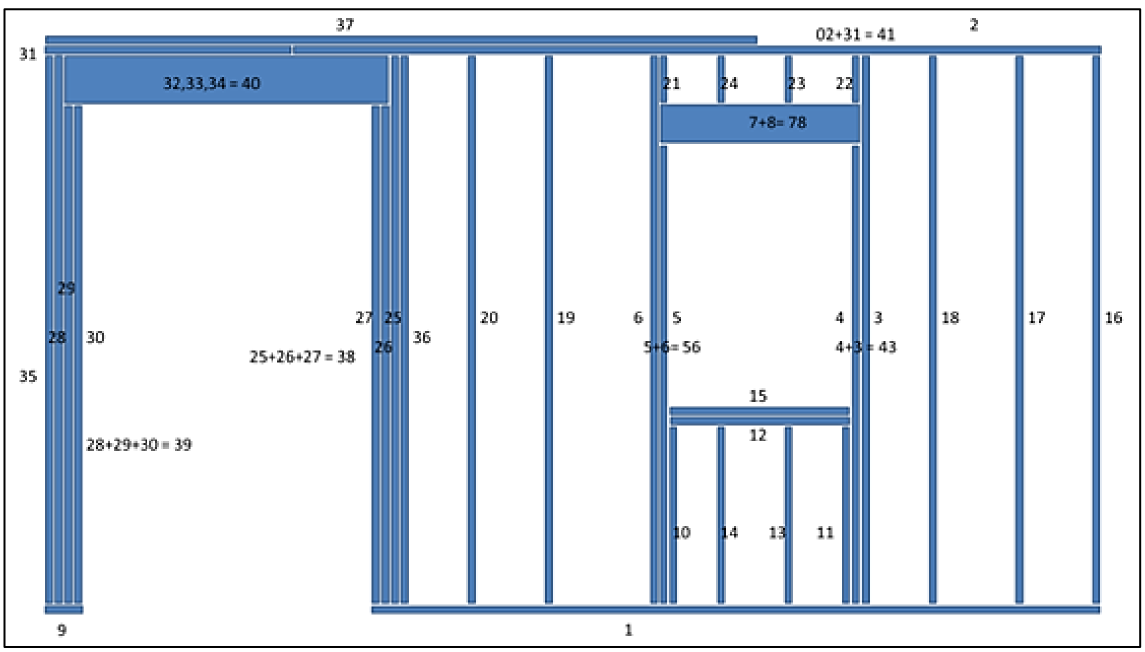
Maghiar (2011) investigated wood framing to understand work task sequencing and the necessary coordination between crew members. His research provides the observation data for this case, it includes detailed data on the construction of load bearing and non-load bearing timber frame walls for residential structures.

The effect of building design in wood framing is evaluated for frames named three and four in Maghiar's work (2011). Figures 11 and Figure 12 are illustrations of the frames with all the elements in place. All elements were assigned unique numbers to delineate them in the frame structure.

There are some situations when two or more elements are nailed together before being placed in the frame. They are named subassemblies.

Figure 11

Illustration of Frame Three



Note. Frame three is composed of 37 elements. It is 8' 10" height and 16' 6" width. Door opening is 54" × 94" and window opening 34" × 48".

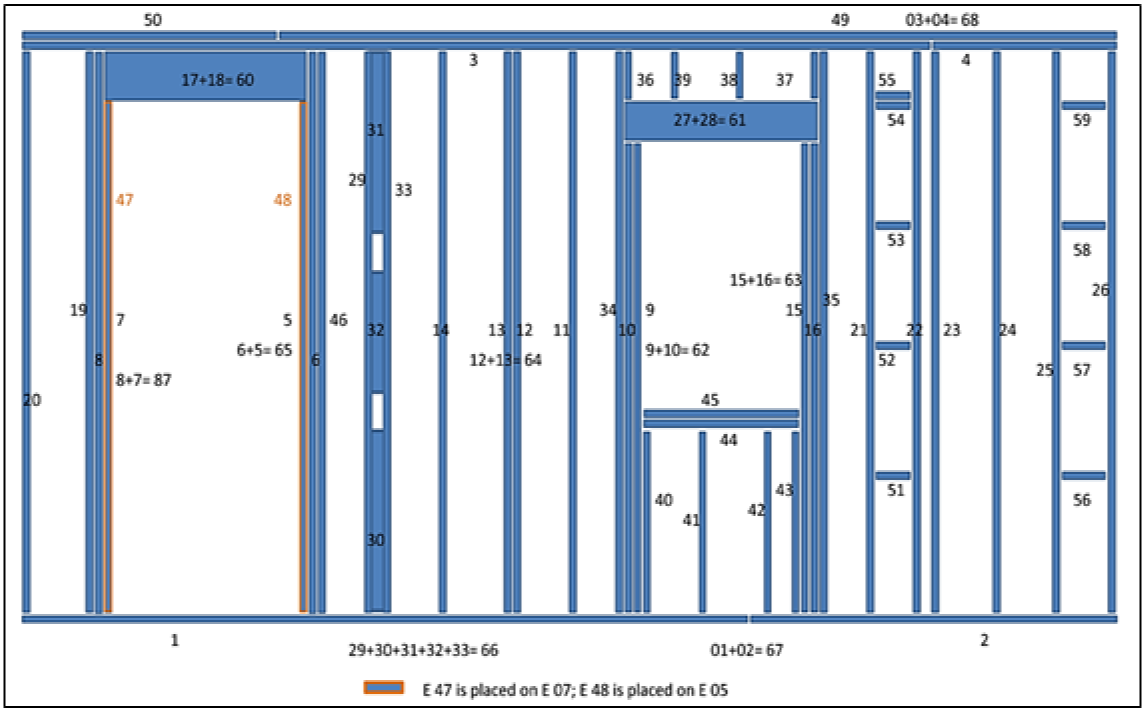
Frame subassemblies: (25+26+27), (28+29+30), (32+33+34), (3+4), (5+6), (7+8), (2+31). Numbers in parentheses identify elements in a subassembly.

From Maghiar (2011).

Frame two in Maghiar´s work was considered as the frame with base design. See an illustration in Figure 13.

Figure 12

Illustration of Frame Four



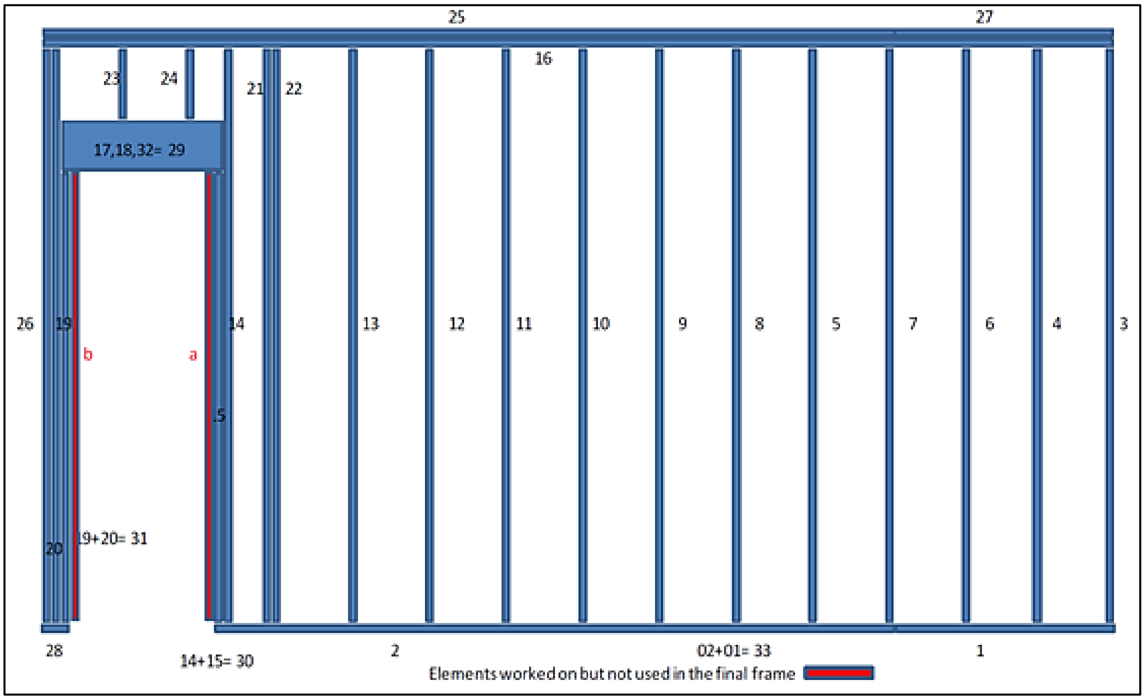
Note. Frame four is composed of 59 elements. It is 8’ 10” height and 19’ 8” width. Door opening is 40” × 94” and window opening 34” × 48”.

Frame subassemblies: (8+7), (6+5), (17+18), (9+10), (15+16), (27+28), (12+13), (29+30+31+32+33), (1+2), (3+4). Numbers in parentheses identify elements in a subassembly.

From Maghiar (2011).

Figure 13

Illustration of Frame with Base Design -Frame Two



Note. Frame with base design is composed of 29 elements. It is 8' 10" height and 18' 8" width. Door opening is 30" × 90".

Frame subassemblies: (19+20), (14+15), (17+18+32), (1+2).). Numbers in parenthesis identify elements in a subassembly.

From Maghiar (2011).

Construction Tasks Required by Wood Framing

Based on the tasks identified by Maghiar (2011) for wood framing, the following tasks were considered as the ones required by this activity:

- Handling
- Measuring
- Marking

- Cutting
- Placing
- Nailing

Tape measuring and in-field measuring were merging in the task measuring.

Relationship Between the Average Productive Time Spent on a Task and the Quantity of Work to be Done.

In Maghiar's study (2011), different crews worked on wood framing. The crew that worked on frame two was identified as crew A, the one that worked on frame three as crew B and finally, the one that worked on frame four as crew C.

Maghiar (2011) analyzed, frame by frame, recorded videos of wood framing work to determine the time spent on each task. Table 5 shows the average productive time per unit of work of the tasks for each crew.

Table 4

Average Productive Time per Unit of Work Required to Carry out the Wood Framing Tasks

Task	Crew A	Crew B	Crew C
Handling	3.6	1.8	1.8
Measuring	5.8	5.4	4.3
Marking	2.6	2.5	1.5
Cutting	3.3	2.4	2.4
Placing	5.4	2.4	2.3
Nailing	6.5	4.6	3.0

Note. The average productive time per unit of work is in seconds per unit of work.

Quantities of Work to be Done on Tasks

The quantities of work to be done in the required construction tasks were determined from the illustrations of the wood frames shown in Figures 11, Figure 12, and Figure13; and data registered in Maghiar's work (2011) work. Table 5 shows the quantities of work for each task and for the three frames.

Table 5

Quantities of Work to be Done on Wood Framing Tasks for each Frame

Task	Frame two	Frame three	Frame four
Handling	29 units	37 units	59 units
Measuring	29 units	37 units	59 units
Marking	29 marks	37 marks	59 marks
Cutting	29 units	37 units	59 units
Placing	25 units	30 units	50 units
Nailing	50 nails	60 nails	100 nails

Average Total Productive Labor Time Spent in Wood Framing.

The average total productive labor time ($Atplt$) for wood framing is evaluated by summing the average productive time spent on each task. This latter can be calculated as the product of the average productivity time per unit of work of a task and the quantity of work to be done to build the frame. That is:

$$Atplt = \sum Aupt_i \times q_i \tag{48}$$

Where:

$Aupt_i =$ is the average productive time per unit of work of task *i*

$q_i =$ is the quantity of work to be done in task *i*

Based on the data registered in Table 4 and 5; and Equation 48 the average total productive labor time for each frame and crew have been calculated (See Table 6).

Table 6

Average Total Productive Labor Time Spent in Wood Framing for Each Frame and Crew

Crew	Task	Frame two			Frame three			Frame four		
		$Aupt_i$	q_i	$Atplt_i$	$Aupt_i$	q_i	$Atplt_i$	$Aupt_i$	q_i	$Atplt_i$
A	Handling	3.6	29	0.029	3.6	37	0.037	3.6	59	0.059
	Taping	5.8	29	0.047	5.8	37	0.060	5.8	59	0.095
	Marking	2.6	29	0.021	2.6	37	0.027	2.6	59	0.043
	Cutting	3.3	29	0.027	3.3	37	0.034	3.3	59	0.054
	Placing	5.4	25	0.038	5.4	30	0.045	5.4	50	0.075
	Nailing	6.5	50	0.090	6.5	60	0.108	6.5	100	0.181
			$Atplt$	0.251		$Atplt$	0.311		$Atplt$	0.506
B	Handling	1.8	29	0.014	1.8	37	0.019	1.8	59	0.029
	Taping	5.4	29	0.044	5.4	37	0.056	5.4	59	0.089
	Marking	2.5	29	0.020	2.5	37	0.026	2.5	59	0.041
	Cutting	2.4	29	0.019	2.4	37	0.025	2.4	59	0.039
	Placing	2.4	25	0.017	2.4	30	0.020	2.4	50	0.033
	Nailing	4.6	50	0.064	4.6	60	0.077	4.6	100	0.128
			$Atplt$	0.178		$Atplt$	0.221		$Atplt$	0.360
C	Handling	1.8	29	0.014	1.8	37	0.019	1.8	59	0.029
	Taping	4.3	29	0.035	4.3	37	0.044	4.3	59	0.071
	Marking	1.5	29	0.012	1.5	37	0.016	1.5	59	0.025
	Cutting	2.4	29	0.019	2.4	37	0.025	2.4	59	0.039
	Placing	2.3	25	0.016	2.3	30	0.019	2.3	50	0.032
	Nailing	3.0	50	0.042	3.0	60	0.050	3.0	100	0.083
			$Atplt$	0.139		$Atplt$	0.172		$Atplt$	0.279

Note. $Aupt_i$ is in seconds per unit of work, $Atplt_i$ is in labor hours.

From Table 6 data, it can be stated that crew C is the most skilled crew. When working on the same frame, they spend less average effective work effort than the others.

Effective Labor Unit Rate

To calculate the effective labor unit rate, the average total productive labor time spent in the execution of tasks must be divided by the amount of produced output (Po).

Based on the dimensions of each frame the produced output has been calculated. For frame two, Po = 13.91 m^2; for frame three, Po = 9.21 m^2; and for frame four, Po = 12.66 m^2.

Table 7 shows the effective labor unit rate for each crew and frame, and the data required for its calculation.

Table 7

Effective Labor Unit Rate of Floor Tiling for Each Frame and Crew

Crew	Frame two			Frame three			Frame four		
	Atplt	*Po*	$Elur_B$	*Atplt*	*Po*	*Elur*	*Atplt*	*Po*	*Elur*
Crew A	0.251	13.91	0.0180	0.311	9.21	0.0338	0.506	12.66	0.0400
Crew B	0.178	13.91	0.0128	0.221	9.21	0.0240	0.360	12.66	0.0284
Crew C	0.139	13.91	0.0100	0.172	9.21	0.0187	0.279	12.66	0.0220

Note. $Atplt$ is in labor hours, Po is in m^2 and $Elur$ in labor hour/m^2.

Indexes of Difficulty

Table 8 shows the values of the indexes of difficulty calculated for each frame and crew using Equation 3 and data from Table 7.

For example, for frame four and crew A, the index of difficulty for wood framing was calculated as:

$$Id = \frac{Elur}{Elur_B} = \frac{0.0400}{0.0180} = 2.215$$

Table 8

Indexes of Difficulty for Wood Framing

Crew	Frame three	Frame four
A	1.871	2.215
B	1.875	2.222
C	1.869	2.205

Table 8 shows that despite the difference in their levels of skills the indexes of difficulty of the wood frames are similar for the three crews. The results also show that the design of frame four has more effect on wood framing than the design of frame three; the index of difficulty of frame four is greater than that of frame three.

Effect of Design on Crews Work

The relative index of difficulty for crews (Rid_C) can be used to compare the effect of frame design on crews' work. For frame three, the effect of its design on the work of crew A in relation to the work of crew C can be calculated from:

$$Rid_C = \frac{0.0180 \times 1.871}{0.0100 \times 1.869} = 1.808$$

From here, it can be stated that the effect of frame three’s design on the work of crew A is 1.81 times greater than its effect on the work of crew C.

Similar calculations can be done to compare the effect of frame three’s design on the work of crew B in relation to the work of crew C. In this case:

$$Rid_C = \frac{0.0128 \times 1.875}{0.0100 \times 1.869} = 1.284$$

The effect of frame three's design on the work of crew B is 1.28 times greater than its effect on the work of crew C. By examining the values of the relative index, it can be asserted that crew A is the most affected by the design of frame three (Rid_C=1.81), followed by crew B (Rid_C=1.28), and finally crew C (Rid_C=1.00, as crew C was used as the baseline for comparison).

Considering that a higher design effect on construction work corresponds to increased work effort and recognizing that an increased work effort is associated with lower skill levels, it can be deduced that crew C possesses the highest level of skills.

Same analysis can be done for frame four. The effect of the design of frame four on the work of crew A in relation to the work of crew C is:

$$Rid_C = \frac{0.0180 \times 2.215}{0.0100 \times 2.205} = 1.814$$

And for crew B in relation to crew C

$$Rid_C = \frac{0.0128 \times 2.215}{0.0100 \times 2.222} = 1.290$$

So, also for frame 4, the crew most affected by the design of the frame is crew A, then crew B and finally crew C. Again, crew C is the one with the highest skills.

The effect of frame design on the work of the group of crews A, B, and C can be calculated using the equation of the index of difficulty of a group of crews (see Equation 31). For frame three, this is:

$$Id = \frac{0.0180 \times 1.871 + 0.0128 \times 1.875 + 0.0100 \times 1.869}{0.0180 + 0.0128 + 0.0100} = 1.872$$

And for frame four:

$$Id = \frac{0.0180 \times 2.215 + 0.0128 \times 2.222 + 0.0100 \times 2.205}{0.0180 + 0.0128 + 0.0100} = 2.215$$

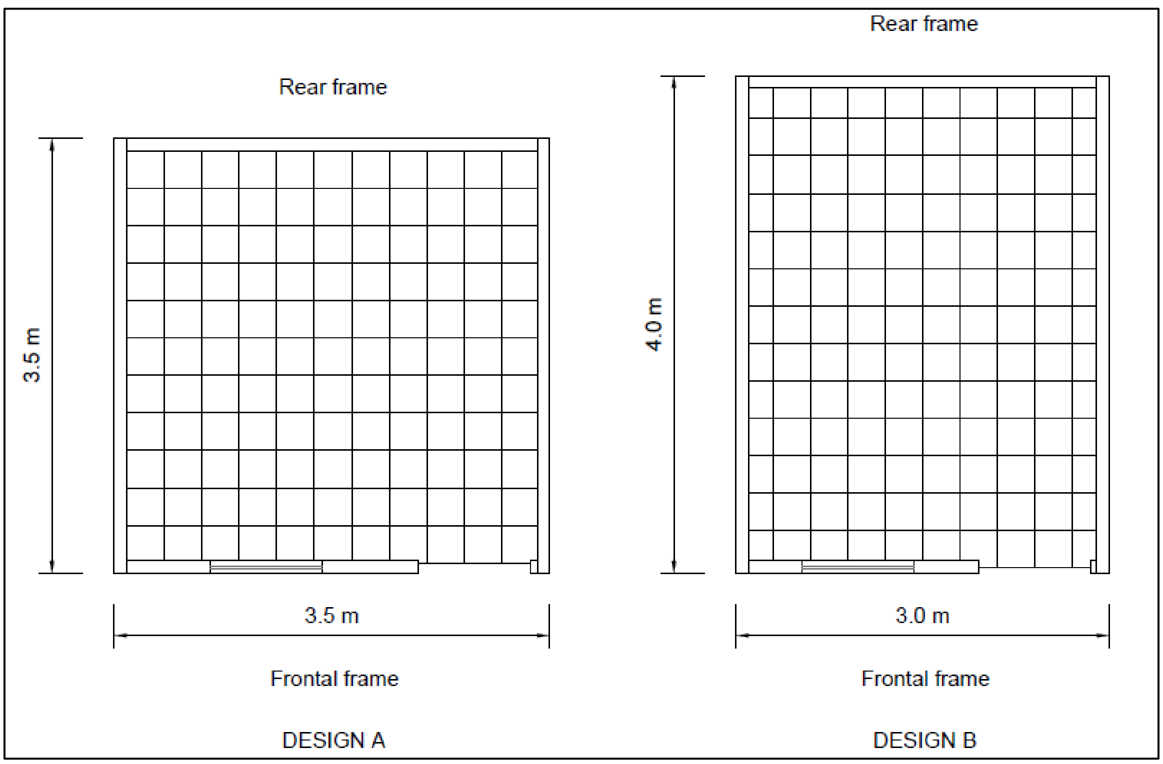
If Crew A, B, and C are the crews of a contractor, these values represent the effect of the wood frame design on the contractor's work and as it is expected are in the range shown in Table 8.

7.3 Application Case C. Comparing the Effect of Design Solutions

Figure 14 shows the plan view of two design solutions for a field office, while Figures 15 and 16 show illustrations of the wood frames of these offices.

Figure 14

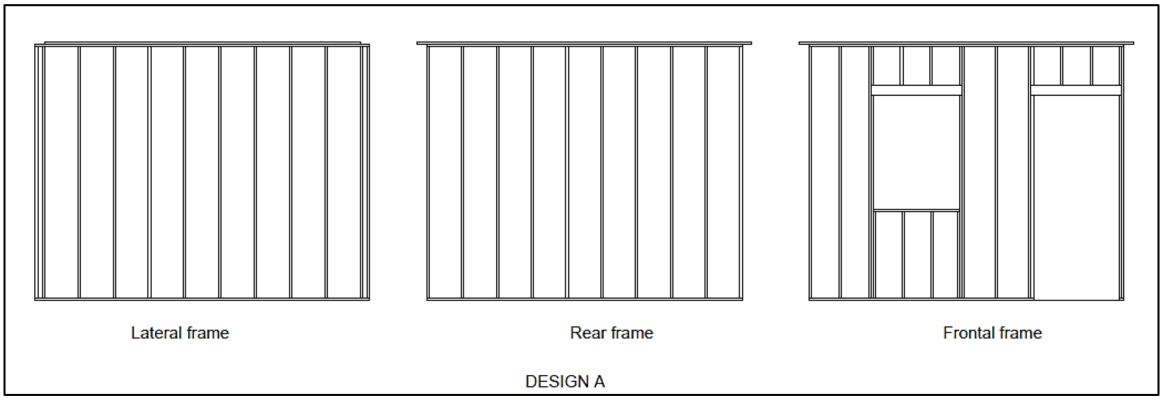
Plan View of Two Design Solution for a Field Office



Note. In both design solutions the floor is covered with square tiles of 30 cm.

Figure 15

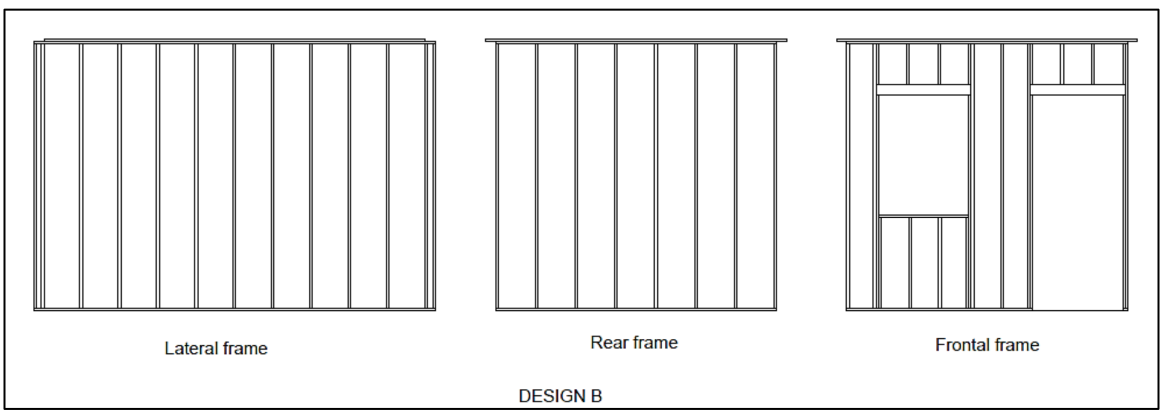
Office Wood Frames for Design Solution A



For design solution A, lateral frames, composed of 15 elements, are 2.7 m. height and 3.5 m. width. The rear frame, composed of 13, is 2.7 m. height and 3.3 m. width. The front frame, composed of 32 elements and 6 subassemblies, is 2.7 m. height and 3.3 m. width. In this latter the door opening is 0.9 m.× 2.15 m., and the window opening is 0.9 m.× 1.2 m.

Figure 16

Office Wood Frames for Design Solution B



For design solution B, lateral frames, composed of 16 elements, are 2.7 m. height and 4.0 m. width. The rear frame, composed of 11 elements, is 2.7 m. height and 2.8 m.

width. The front frame, composed of 31 elements and 6 subassemblies, is 2.7 m. height and 2.8 m. width. In this latter the door opening is 0.9 m. × 2.15 m., and the window opening is 0.9 m. × 1.2 m.

The effect of these design solutions for floor finishing and wood frame on floor tiling and wood framing work has been compared. The relative index of difficulty for families, and groups of families have been used for this purpose.

Comparison of Floor Tile Design Solutions Effect on its Construction Work

The base construction part defined in case A was used for comparing the effect of floor tile design solutions on construction work. Then for the base design, Po =16.0 m^2, and $Elur_B = 0.444 \text{ labor} - \text{hours/m}^2$.

Using computer-aided design software the corresponding number of uncut tiles, tiles with one cut, tiles with two cuts, tiles with three cuts, the length of cutting, and the area of the construction part were determined from digital drawings. Figure 17 and Figure 18 show the data for each design solution. The relative representative area of a cut tile is the average area of a cut tile divided by the area of an uncut tile.

Figure 17

Tile Floor Quantities for Field Office Design Solution A

Design A	30x30 cm	3.50 x 3.50	Area =	10.91	m2
Total tiles	121				
Uncut tiles	102				
Cut tiles	19				

Cut tiles	Quantities	Relative representative area	Cutting length (cm)
One cut	17	0.97	510
Two cuts	1	0.97	25
Three cuts	1	0.96	36

Figure 18

Tile Floor Quantities for Field Office Design Solution B

Design B	30x30 cm	4.00 x 3.00	Area =	10.69	m2
Total tiles	130				
Uncut tiles	90				
Cut tiles	40				

Cut tiles	Quantities	Relative representative area	Cutting length (cm)
One cut	35	0.71	1050
Two cuts	4	0.62	152
Three cuts	1	0.62	41

For both design solutions, the average total productive labor time required for floor tiling has been determined using the average productive times per unit of work from Table 2 and the quantities presented in Figure 17 and Figure 18. Figure19 and Figure 20 show the data and partial results of these calculations.

To calculate the effective labor unit rate, the average total productive labor time spent in the execution of tasks must be divided by the amount of produced output (Po).

For design solution A, $Atplt$ = 4.30 labor -hours and Po =10.91 m^2, then

$$Elur = \frac{4.30 \text{ labor} - \text{hours}}{10.91\text{m}^2} = 0.394 \text{ labor} - \text{hours/m}^2$$

For design solution B, $Atplt$ = 4.91 labor -hours and Po =10.69 m^2, then

$$Elur = \frac{4.91 \text{ labor} - \text{hours}}{10.69\text{m}^2} = 0.459 \text{ labor} - \text{hours/m}^2$$

Then for floor tiling, the index of difficulty of floor finish for design solution A is:

$$Id = \frac{Elur}{Elur_B} = \frac{0.394 \text{ labor} - \text{hours}}{0.444 \text{ labor} - \text{hours}} = 0.888$$

And for design solution B:

$$Id = \frac{Elur}{Elur_B} = \frac{0.459 \text{ labor} - \text{hours}}{0.444 \text{ labor} - \text{hours}} = 1.034$$

Figure 19

Calculation of the Average Total Productive Labor Time Required by Floor Tiling for Design Solution A

Design A							
Tile dimension	30x30						
Area	10.91 m2						
Tile pieces information							
Tile information		Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Four cuts tiles	Totals
Number of pieces		102	17	1	1	0	121
Cut length (cm)			510	25	36	0	571
Productive time for cutting tiles							
Task	Average productivity time per unit		One cut tiles	Two cuts tiles	Three cuts tiles	Four cuts tiles	Productive time (hour)
Handling tiles	20 sec/piece		340	20	20	0	0.11
Measuring tiles	10 sec/point		340	40	60	0	0.12
Marking tiles	0.2 sec/cm		102	5	7.2	0	0.03
Setting tiles	4 sec/piece		68	4	4	0	0.02
Cutting tiles	1 sec/cm		510	25	36	0	0.16
Storing tiles	10 sec/piece		170	10	10	0	0.05
							0.49
Productive time for installing tiles							
Task	Average productivity time per unit	Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Four cuts tiles	Productive time (hour)
Preparing adhesive	120 sec/m2						0.36
Spreading adhesive	300 sec/m2						0.91
Handling tiles	20 sec/piece	2040	340	20	20	0	0.67
Positioning tiles	5 sec/piece		85	5	5	0	0.03
Setting tiles	55 sec/piece	5610	907	54	53	0	1.84
							3.81
Average total productive labor time = 0.49 + 3.81 = 4.30 labor hours							4.30

Figure 20

Calculation of the Average Total Productive Labor Time Required by Floor Tiling for Design Solution B

Design B							
Tile dimension	30x30						
Area	10.69 m2						
Tile pieces information							
Tile information		Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Four cuts tiles	Totals
Number of pieces		90	35	4	1	0	130
Cut length (cm)			1050	152	41	0	1243
Productive time for cutting tiles							
Task	Average productivity time per unit		One cut tiles	Two cuts tiles	Three cuts tiles	Four cuts tiles	Productive time (hour)
Handling tiles	20 sec/piece		700	80	20	0	0.22
Measuring tiles	10 sec/point		700	160	60	0	0.26
Marking tiles	0.2 sec/cm		210	30	8.2	0	0.07
Setting tiles	4 sec/piece		140	16	4	0	0.04
Cutting tiles	1 sec/cm		1050	152	41	0	0.35
Storing tiles	10 sec/piece		350	40	10	0	0.11
							1.05
Productive time for installing tiles							
Task	Average productivity time per unit	Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Four cuts tiles	Productive time (hour)
Preparing adhesive	120 sec/m2						0.36
Spreading adhesive	300 sec/m2						0.89
Handling tiles	20 sec/piece	1800	700	80	20	0	0.72
Positioning tiles	5 sec/piece		175	20	5	0	0.06
Setting tiles	55 sec/piece	4950	1463	152	37	0	1.83
							3.86
Average total productive labor time = 1.05 + 3.86 = 4.91 labor hours							4.91

To compare the effect of the design solutions on floor tiling, the following equation for the relative index of difficulty of construction part families is used:

$$Rid_f = \frac{Po_{ij} \times Id_{ij}}{Po_{ij} \times Id_{ij}} = \frac{10.91 \times 0.888}{10.69 \times 1.034} = 0.88$$

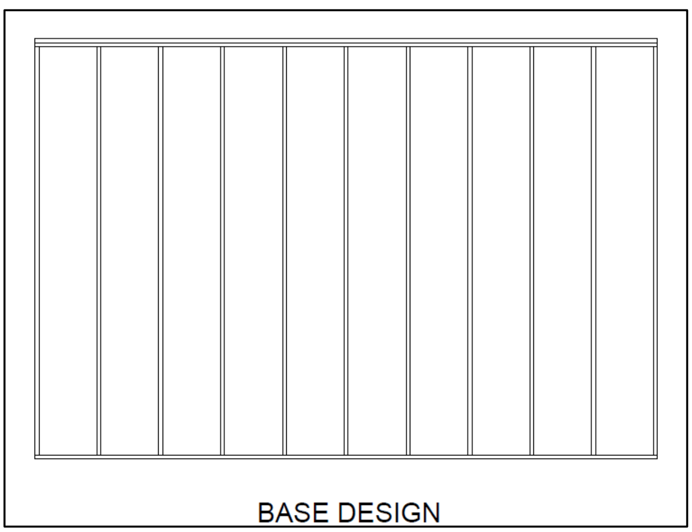
The value of Rid_f below 1 indicates that the effect of design solution A on floor tiling is lower than the effect of design solution B on this activity. The value also implies that, for floor tiling, design solution A demands less effective work effort than design solution B.

Comparison of Wood Frame Design solutions effect on its construction work

For comparing the effect of wood frame design solutions on construction work, it has been taken as the base construction part, a frame composed of 14 elements; it is 2.7 m. height and 4.0 m. width (see Figure 21).

Figure 21

Illustration of the Base Wood Frame for Wood Framing



The quantities of work to be done in the required construction tasks were determined from the illustration of wood frame shown on Figures 21 for base design (see Table 9), on Figure 15 for design A (see Table 10), and on Figure 16 for design B (see Table 11).

Table 9

Quantities of Work to be Done in the Base Frame

Task	Base frame
Handling	14 units
Taping	14 units
Marking	14 marks
Cutting	14 units
Placing	14 units
Nailing	28 nails

Table 10

Quantities of Work to be Done in Frames for Design Solution A

Task	Lateral frame	Rear frame	Frontal frame
Handling	15 units	13 units	32 units
Taping	15 units	13 units	32 units
Marking	15 marks	13 marks	32 marks
Cutting	15 units	13 units	32 units
Placing	15 units	13 units	26 units
Nailing	30 nails	26 nails	52 nails

Table 11

Quantities of Work to be Done in Frames for Design Solution B

Task	Lateral frame	Rear frame	Frontal frame
Handling	16 units	11 units	31 units
Taping	16 units	11 units	31 units
Marking	16 marks	11 marks	31 marks
Cutting	16 units	11 units	31 units
Placing	16 units	11 units	25 units
Nailing	33 nails	22 nails	50 nails

Table 12 shows the average unit productive time of the tasks used for the calculation of the average total productive labor time. They correspond to the average for crews A, B and C from case B.

Table 12

Average Productive Time per Unit of Work Required to Carry out the Wood Framing Tasks

Task	$Aupt$
Handling	2.4
Taping	5.1
Marking	2.2
Cutting	2.7
Placing	3.4
Nailing	4.7

Note. The average productive time per unit work is in second per unit of work.

The average total productive labor time ($Atplt$) for wood framing is evaluated by summing the average productive time spent on each task. This latter can be calculated as the product of the average productivity time per unit of work of a task and the quantity of work to be done to build the frame.

Based on the data presented in Table 9, Table 10, Table 11, and Table 12; and Equation 44 the average total productive labor time for each frame have been calculated (See Table 13, Table 14, and Table 15).

Table 13

Average Total Productive Labor Time for Base Frame

Task	Base frame		
	$Aupt_i$	q_i	$Atplt_i$
Handling	2.4	14	0.009
Taping	5.1	14	0.020
Marking	2.2	14	0.009
Cutting	2.7	14	0.011
Placing	3.4	14	0.013
Nailing	4.7	28	0.037
		$Atplt$	0.098

Note. $Aupt_i$ is in seconds per unit of work, $Atplt_i$ is in labor hours.

Table 14

Average Total Productive Labor Time for Frame Design Solution A

Task	$Aupt_i$	Lateral frame		Rear frame		Frontal frame	
		q_i	$Atplt_i$	q_i	$Atplt_i$	q_i	$Atplt_i$
Handling	2.4	15	0.010	13	0.009	32	0.021
Taping	5.1	15	0.021	13	0.018	32	0.045
Marking	2.2	15	0.009	13	0.008	32	0.019
Cutting	2.7	15	0.011	13	0.010	32	0.024
Placing	3.4	15	0.014	13	0.012	26	0.024
Nailing	4.7	30	0.039	26	0.034	52	0.068
		$Atplt$	0.105	$Atplt$	0.091	$Atplt$	0.202

Note. $Aupt_i$ is in seconds per unit of work, $Atplt_i$ is in labor hours.

Table 15

Average Total Productive Labor Time for Frame Design Solution B

Task	$Aupt_i$	Lateral frame		Rear frame		Frontal frame	
		q_i	$Atplt_i$	q_i	$Atplt_i$	q_i	$Atplt_i$
Handling	2.4	16	0.011	11	0.007	31	0.021
Taping	5.1	16	0.023	11	0.016	31	0.044
Marking	2.2	16	0.010	11	0.007	31	0.019
Cutting	2.7	16	0.012	11	0.008	31	0.023
Placing	3.4	16	0.015	11	0.010	25	0.024
Nailing	4.7	32	0.042	22	0.029	50	0.065
		$Atplt$	0.112	$Atplt$	0.077	$Atplt$	0.196

Note. $Aupt_i$ is in seconds per unit of work, $Atplt_i$ is in labor hours.

To calculate the effective labor unit rate, the average total productive labor time spent in the execution of tasks must be divided by the amount of produced output (Po). Based on the dimensions of each frame the produced output has been calculated for both design solutions.

Table 16 shows the effective labor unit rate of wood framing and the data required for its calculation for each crew and each design solution.

Table 16

Effective Labor Unit Rate of Wood Framing for Each Frame

Design	Lateral frame			Rear frame			Frontal frame		
	Atplt	*Po*	*Elur*	*Atplt*	*Po*	*Elur*	*Atplt*	*Po*	*Elur*
A	0.105	9.45	0.0111	0.091	8.91	0.0102	0.202	5.90	0.0343
B	0.112	10.80	0.0103	0.077	7.56	0.0101	0.196	4.55	0.0430

Note. $Atplt$ is in labor hours, Po is in m^2 and $Elur$ in labor hour/m^2.

In the case of base design $Atplt$ = 0.098 labor -hours and Po =10.80 m^2, then

$$Elur_B = \frac{0.098\ \mathrm{labor-hours}}{10.80\mathrm{m}^2} = 0.0091\ \mathrm{labor-hours/m}^2$$

Table 17 shows the values of the indexes of difficulty calculated for each frame and for both design solutions using Equation 3. It also shows the cumulative produced output and the cumulative index of difficulty of the wood frames for each design solution.

Table 17

Indexes of Difficulty and Cumulative Index of Difficulty for Wood Framing

Design		Id		Cpo	Cid
	Lateral frame	Rear frame	Front frame	(m^2)	
A	1.224	1.120	3.768	33.71	1.641
B	1.136	1.114	4.726	33.71	1.615

For design solution A, the cumulative produced output for wood framing was calculated as:

$$Cpo = 2 \times 9.45 + 8.91 + 5.90 = 33.71\ m^2$$

And the cumulative index of difficulty of wood frames as:

$$Cid = \frac{2 \times 9.45 \times 1.224 + 8.91 \times 1.120 + 5.90 \times 3.768}{33.71} = 1.641$$

Same calculations were made for design solution B.

To compare the effect of the design solution on floor tiling the following equation for the relative index of difficulty of construction part families was used:

$$Rid_f = \frac{Aewe_{FA}}{Aewe_{FB}}$$

From equation 42

$$Aewe_{FA} = \sum_{i \in \{F_A A\}} Elur_{Bi} \times Cpo_i \times Cid_i$$

Replacing for design solution A and B

$$Aewe_{FA} = 0.0091 \times 33.71 \times 1.641 = 0.504$$

$$Aewe_{FB} = 0.0091 \times 33.71 \times 1.615 = 0.496$$

Then

$$Rid_f = \frac{0.504}{0.496} = 1.02$$

The value of Rid_f close to 1 indicates that the effect of design solution A on wood framing is nearly the same to the effect of design solution B on this activity. That is, for wood framing, design solution A and B require a similar effective work effort.

Comparison of Floor tile and wood frame design solutions effect on its construction work

For both design solutions, the indexes of difficulty can be calculated for the required construction activities (e.g., excavations, formwork, rebar, concrete, floor tiling, wood framing, door installation, etc.) by all the construction parts (slab on grade, floor finishing, wood frames, door, window, etc.) following procedures similar to ones previously showed. These indexes can be arranged in a matrix $[Id]$ to express the difficulty of performing the construction activities for both designs.

For design solution A, the submatrix of the matrix of the indexes of difficulty corresponding to floor finishing (column 1) and wood frames (columns 2: left frame, column 3: rear frame, column 4: right frame, column 5: front frame) for floor tiling (row 1) and wood framing (row 2) is expressed as:

$$[Id_A] = \begin{bmatrix} 0.888 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 1.224 & 1.120 & 1.224 & 3.768 \end{bmatrix}$$

And for design solution B:

$$[Id_B] = \begin{bmatrix} 1.034 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 1.136 & 1.114 & 1.136 & 4.726 \end{bmatrix}$$

Indexes of difficulty corresponding to floor finishing for both design solutions were determined previously (see page 103 for design solution A and page 104 for design solution B). Table 17 shows the indexes of difficulty corresponding to wood framing for both design solutions.

Values of the indexes in the submatrix $[Id_A]$ for wood framing (second row) allow to identify the wood frame design (front frame) with the greatest effect on wood framing (Id = 3.768 for design solution A).

A comparison of the effect of the two design solutions for floor finishing on floor tiling has been presented. The same was done for wood frames on wood framing. Similar procedures can be followed to compare the effect of the design of other construction parts families on its construction work.

To compare the effect of the design solutions A and B for floor finishing and wood frame on its construction work, the relative index of difficulty of groups of construction parts families should be used:

$$Rid_g = \frac{\sum_{k\in\{G_A F\}} Aewe_{Fk}}{\sum_{k\in\{G_B F\}} Aewe_{Fk}}$$

Table 18 shows the average effective work effort required for floor finishing and wood frames for both design solutions.

Table 18

Average Effective Work Effort for Design Solution A and Design Solution B

Design solution	Average effective work effort	
	Floor finishing	Wood frames
A	4.304	0.504
B	4.907	0.496

The calculation of the average effective work effort (or average total productive labor time) for floor finishing is illustrated in Figures 19 and 20 for each respective design alternative. The calculation of the average effective work effort for wood framing for each design solution can be found on page 112.

Then for the application case, replacing on the expression for Rid_g

$$Rid_g = \frac{4.304 + 0.504}{4.907 + 0.496} = 0.89$$

The effect of design solution A on floor tiling and wood framing is lower than the effect of design solution B on these activities.

This form of assessment can be broadened to encompass all families of construction parts as well as the required construction activities. In this scenario, the summation for Rid_g calculation should incorporate the average effective work effort of all the construction activities demanded by each construction part family.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The approach described in this document provides a quantitative means that allows measuring the effect of building design on construction work supported by field data. As design features of the building components or construction parts are the expression of building design, the effect of building design is evaluated on the work done to complete any construction activity required by a construction part.

The effect of a construction part design corresponds to the effect of the set of design features that define the construction part. The horizon of evaluation of this effect is not time-based (i.e., hourly, daily, etc.), it is related to the completion of the construction part, hence the total effect can be evaluated.

The effective labor unit rate captures properly the effect of design on construction work. It relates the design of a construction part with the effective work effort needed to accomplish the works required by the construction part per unit of produced output. Hence, a greater effective labor unit rate means a greater effect of the construction part design on a construction activity. The effective work effort must be calculated considering only the time crew members are working avoiding the effect of interruption or management issues, but also as an average given that productive time is not deterministic. If a crew performs a construction activity many times, the average productive time spent in the activity trends to one unique value, the means of this aleatory variable. Given the non-deterministic behavior of construction working time, the index of difficulty must be understood as an expected value. The index is also ignoring the effect of the learning curve on productivity. Complexity is considered at the productivity level achieved after multiple repetitions.

The average productive labor time to complete a construction activity is determined by adding the average productive times of the tasks required to complete the construction activity. So, for the purpose of measuring the effect of design, the main attention is on developing models that relate the average productive time of a task to the quantity of work to be done through the task. Since, the design of the construction part to be done determines the task to be done, and the quantity of work to be done, having these models allow for determining the average productive time of different design of a construction part and therefore measuring their effect. For the development of models, observation at the task level allows better identification of outliers and the exclusion of measurements from abnormal conditions. These models will also allow analyzing the effect of a given design feature on construction work and gain some insights into its behavior.

Comparison is key for measuring the effect of design on construction work. The index of difficulty relates the effective labor unit rate for two design conditions, one whose effect is going to be evaluated and one that is considered the base of comparison. This relative measure allows measuring the effect of design on the construction work in many ways. With this index, the relative effect of design features of a construction part on the work carried out in construction activities can be calculated, a greater index represents a greater effect of design. For each construction activity, cumulative indexes of difficulty of a set of construction parts can be calculated, but also the index of each construction part and the cumulative index of a set of construction parts. The construction activity most affected by design and the construction part with the greatest effect on construction work can be identified.

Additionally, a relative index of difficulty can be used for the relative evaluation of crew skills, and the identification of the means and methods that demand less work effort, among the one available to carry out a construction activity. A relative index of difficulty can also be used to compare the effect of design solutions on their required work.

Application case B showed that the effect of the crew's skill on the value of the index of difficulty is reduced. This could be the consequence of considering simultaneously in the numerator and the denominator, the effect of the same crew on the work effort required, that is, of calculating the effective labor unit rate for the same crew.

Recommendations

The implementation of the proposed concepts should be, initially, focused on its application to construction activities, studying the effect of the design, progressively, in different construction parts. The set of facts found, then, can become knowledge that can assist decisions. In this process, it will be found that for some construction activities, this conception is more easily applied than in others and that the effect of design on some of these activities could not be appreciable.

Calculation of an index of difficulty requires detailed design information and quantity take-off. The development of specific BIM tools will facilitate the evaluation of the index of difficulty.

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APPENDIX A

MATRIX CALCULATIONS OF THE CUMULATIVE INDEX OF DIFFICULTY

Matrix Calculations for Row and Column Matrixes of Indexes of Difficulty

Given a matrix arrangement $[Id]$ of the indexes of difficulty of the construction parts of a building for their required construction activities.

$$[Id] = \begin{bmatrix} Id_{1,1} & Id_{1,2} & Id_{1,3} & \dots & Id_{1,j} & \dots & Id_{1,m} \\ Id_{2,1} & Id_{2,2} & Id_{2,3} & \dots & Id_{2,j} & \dots & Id_{2,m} \\ Id_{3,1} & Id_{3,2} & Id_{3,3} & \dots & Id_{3,j} & \dots & Id_{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Id_{i,1} & Id_{i,2} & Id_{i,3} & \dots & Id_{i,j} & \dots & Id_{i,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Id_{n,1} & Id_{n,2} & Id_{n,3} & \dots & Id_{n,j} & \dots & Id_{n,m} \end{bmatrix}_{n\times m}$$

Where n is the total number of construction activities and m is the total number of construction parts.

Row and column matrix of indexes of difficulty can be obtained using matrix operations.

If $[k_r]^T = [0 \quad 0 \quad 0 \quad \dots \quad 1 \quad \dots \quad 0]_{1\times n} \qquad k_i = 0\ \forall i \neq r\ \wedge\ k_r = 1$

Then, the row matrix of indexes of difficulty related to a construction activity *i* can be obtained from:

$[Id_{ri}] = [k_r]^T[Id]$

$[Id_{ri}] = [Id_{i,1} \quad Id_{i,2} \quad Id_{i,3} \quad \dots \quad Id_{i,j} \quad \dots \quad Id_{i,m}]$ is a row matrix of $1 \times m$

If $[k_c] = [0 \quad 0 \quad 0 \quad \dots \quad 1 \quad \dots \quad 0]_{1\times m} \qquad k_j = 0\ \forall j \neq c\ \wedge\ k_c = 1$

Then, the column matrix of indexes of difficulty related to a construction part *j* can be obtained from:

$$[Id_{cj}] = [Id][k_c]^T$$

$[Id_{cj}]^T = [Id_{1,j} \quad Id_{2,j} \quad Id_{3,j} \quad \dots \quad Id_{i,j} \quad \dots \quad Id_{n,j}]$ is a column matrix of $n \times 1$

Matrix Calculations of the Cumulative Index of difficulty

The weights used for calculations of the cumulative index of difficulty can be arranged in a matrix disposition. If so, $Po_{i,j}$ is the weight corresponding to the construction part *j* and the construction activity *i*

$$[\text{w}] = \begin{bmatrix} Po_{1,1} & Po_{1,2} & Po_{1,3} & \dots & Po_{1,j} & \dots & Po_{1,m} \\ Po_{2,1} & Po_{2,2} & Po_{2,3} & \dots & Po_{2,j} & \dots & Po_{2,m} \\ Po_{3,1} & Po_{3,2} & Po_{3,3} & \dots & Po_{3,j} & \dots & Po_{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Po_{i,1} & Po_{i,2} & Po_{i,3} & \dots & Po_{i,j} & \dots & Po_{i,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Po_{n,1} & Po_{n,2} & Po_{n,3} & \dots & Po_{n,j} & \dots & Po_{n,m} \end{bmatrix}_{nxm}$$

or $$[\text{w}] = \begin{bmatrix} w_{r1} \\ w_{r2} \\ w_{r3} \\ \vdots \\ w_{ri} \\ \vdots \\ w_{rn} \end{bmatrix}_{n\times m}$$

Where:

$$[w_{ri}] = [Po_{i,1} \quad Po_{i,2} \quad Po_{i,3} \quad \dots \quad Po_{i,j} \quad \dots \quad Po_{i,m}]$$

Given a set of construction part identified by a set of indices $\{P\}$

If [D] is a diagonal matrix of order *m*

$$[D] = \begin{bmatrix} D_{11} & 0 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & D_{22} & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & D_{31} & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & D_{ii} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & \dots & D_{mm} \end{bmatrix}$$

$D_{i,i} = 1 \;\; \forall\, i \; \in \; \{P\}$. In other case $D_{i,i} = 0$

And $[r]$ is a row matrix of $1 \times m$ of 1s. That is $[r] = [1 \quad 1 \quad 1 \quad \dots \quad 1]_{1\times m}$

Then, for this set of similar construction parts, the cumulative index of difficulty for the activity i (Cid) can be expressed also as:

$$Cid = \frac{[w_{ri}][D][Id_{ri}]^T}{[w_{ri}][D][r]^T}$$

APPENDIX B

CASE A. TILE FLOOR QUANTITIES FOR CONSTRUCTION PARTS

Figure B1

Tile Floor Quantities for Office Rooms 1

Office rooms 1	30x30 cm	Area =	96.19	m2
Total tiles	1120			
Uncut tiles	980			
Cut tiles	140			

One cut	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	67	18.5	x	30.0	30.0	2010
	52	30.0	x	15.5	30.0	1560
	4	30.0	x	17.5	30.0	120
	4	26.0	x	30.0	30.0	120
	127					3810

Two cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	4	18.5	x	15.5	34.0	136
	3	18.5	x	17.5	36.0	108
	1	26.0	x	17.5	43.5	44
	4	-6.5	x	-12.5	19.0	76
	12					364

Three cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	1	26.0				
		18.5	x	12.0	41.5	42
	1					42
					Total cutting length (cm)	4215

Figure B2

Tile Floor Quantities for Office Rooms 2

Office rooms 2	45x45 cm	Area =	71.98	m2
Total tiles	380			
Uncut tiles	302			
Cut tiles	78			

One cut	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	32	22.0	x	45.0	45.0	1440
	30	45.0	x	29.0	45.0	1350
	2	45.0	x	36.5	45.0	90
	64					2880

Two cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	2	22.0	x	29.0	51.0	102
	2	22.0	x	43.5	65.5	131
	2	22.0	x	22.0	44.0	88
	2	22.0	x	29.0	51.0	102
	2	-32.5	x	-1.5	34.0	68
	2	-32.5	x	-23.0	55.5	111
	12					602

Three cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	1	36.5				
		29.0	x	21.5	61.0	61
	1	36.5				
		29.0	x	11.0	61.0	61
	2					122
					Total cutting length (cm)	3604

Figure B3

Tile Floor Quantities for Office Rooms 3

Office rooms 3	30x30 cm		Area =	24.94	m2
Total tiles	304				
Uncut tiles	230				
Cut tiles	74				

One cut	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	16	18.5	x	30.0	30.0	480
	43	30.0	x	17.5	30.0	1290
	2	30.0	x	21.0	30.0	60
	3	30.0	x	25.0	30.0	90
	64					1920

Two cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	2	18.5	x	17.5	36.0	72
	2	18.5	x	21.0	39.5	79
	2	23.5	x	17.5	41.0	82
	2	-6.0	x	-8.5	14.5	29
	8					262

Three cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	2	25.0				
		17.5	x	15.0	42.5	85
	2					85
					Total cutting length (cm)	2267

Figure B4

Tile Floor Quantities for Corridor

Corridor	30x30 cm		Area =	44.75	m2
Total tiles	567				
Uncut tiles	395				
Cut tiles	172				

One cut	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	152	17.0	x	30.0	30.0	4560
	5	30.0	x	25.5	30.0	150
	5	30.0	x	8.0	30.0	150
	4	30.0	x	24.5	30.0	120
	166					4980

Two cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	2	17.0	x	25.5	42.5	85
	2	17.0	x	8.0	25.0	50
	4					135

Three cuts	**Quantities**	**Representative dimensions**			**Cutting length (cm)**	**Partial**
	1	25.0				
		17.0	x	17.5	43.0	43
	1	25.0				
		17.0		12.0	43.0	43
	2					86
					Total cutting length (cm)	5201

APPENDIX C

CASE A. AVERAGE TOTAL PRODUCTIVE LABOR TIME CALCULATIONS

Figure C1

Calculation of the Average Total Productive Labor Time Required by Floor Tiling for Office Rooms 1

Office rooms 1
Tile dimension 30x30
Area 96.19 m2

Tile pieces information

Tile information		Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Totals
Number of pieces		980	127	12	1	1120
Cut length (cm)			3810	364	42	4215

Productive time for cutting tiles

Task	Average productivity time per unit		One cut tiles	Two cuts tiles	Three cuts tiles	Productive time (hour)
Handling tiles	20 sec/piece		2540	240	20	0.78
Measuring tiles	10 sec/point		2540	480	60	0.86
Marking tiles	0.2 sec/cm		762	73	8.3	0.23
Setting tiles	4 sec/piece		508	48	4	0.16
Cutting tiles	1 sec/cm		3810	363.5	41.5	1.17
Storing tiles	10 sec/piece		1270	120	10	0.39
						3.58

Productive time for installing tiles

Task	Average productivity time per unit	Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Productive time (hour)
Preparing adhesive	120 sec/m2					3.21
Spreading adhesive	300 sec/m2					8.02
Handling tiles	20 sec/piece	19600	2540	240	20	6.22
Positioning tiles	5 sec/piece		635	60	5	0.19
Setting tiles	55 sec/piece	53900	4547	398	42	16.36
						34.00
Average total productive labor time = 3.58 + 34.00 = 37.58 labor hours						37.58

Figure C2

Calculation of the Average Total Productive Labor Time Required by Floor Tiling for Office Rooms 2

Office rooms 2
Tile dimension 45x45
Area 71.98 m2

Tile pieces information

Tile information		**Uncut tiles**	**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Totals**
Number of pieces		302	64	12	2	380
Cut length (cm)			2880	602	122	3604

Productive time for cutting tiles

Task	**Average productivity time per unit**	**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Productive time (hour)**
Handling tiles	20 sec/piece	1280	240	40	0.43
Measuring tiles	10 sec/point	1280	480	120	0.52
Marking tiles	0.2 sec/cm	576	120	24	0.20
Setting tiles	4 sec/piece	256	48	8	0.09
Cutting tiles	1 sec/cm	2880	602	122	1.00
Storing tiles	10 sec/piece	640	120	20	0.22
					2.46

Productive time for installing tiles

Task	**Average productivity time per unit**	**Uncut tiles**	**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Productive time (hour)**
Preparing adhesive	120 sec/m2					2.40
Spreading adhesive	300 sec/m2					6.00
Handling tiles	20 sec/piece	6040	1280	240	40	2.11
Positioning tiles	5 sec/piece		320	60	10	0.11
Setting tiles	110 sec/piece	33220	4512	737	167	10.73
						21.35
Average total productive labor time = 2.46 + 21.35 = 23.81 hours						23.81

Figure C3

Calculation of the Average Total Productive Labor Time Required by Floor Tiling for Office Rooms 3

Office rooms 3
Tile dimension 30x30
Area 24.94 m2

Tile pieces information

Tile information	**Uncut tiles**	**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Totals**
Number of pieces	230	64	8	2	304
Cut length (cm)		1920	262	85	2267

Productive time for cutting tiles

Task	**Average productivity time per unit**	**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Productive time (hour)**
Handling tiles	20 sec/piece	1280	160	40	0.41
Measuring tiles	10 sec/point	1280	320	120	0.48
Marking tiles	0.2 sec/cm	384	52	17	0.13
Setting tiles	4 sec/piece	256	32	8	0.08
Cutting tiles	1 sec/cm	1920	262	85	0.63
Storing tiles	10 sec/piece	640	80	20	0.21
					1.93

Productive time for installing tiles

Task	**Average productivity time per unit**	**Uncut tiles**	**One cut tiles**	**Two cuts tiles**	**Three cuts tiles**	**Productive time (hour)**
Preparing adhesive	120 sec/m2					0.83
Spreading adhesive	300 sec/m2					2.08
Handling tiles	20 sec/piece	4600	1280	160	40	1.69
Positioning tiles	5 sec/piece		320	40	10	0.10
Setting tiles	55 sec/piece	12650	2369	270	84	4.27
						8.97
Average total productive labor time = 1.93 + 8.97 = 10.90 hours						10.90

Figure C4

Calculation of the Average Total Productive Labor Time Required by Floor Tiling for Corridor

Corridor
Tile dimension 30x30
Area 44.75 m2

Tile pieces information

Tile information	Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Totals
Number of pieces	395	166	4	2	567
Cut length (cm)		4980	135	86	5201

Productive time for cutting tiles

Task	Average productivity time per unit	One cut tiles	Two cuts tiles	Three cuts tiles	Productive time (hour)
Handling tiles	20 sec/piece	3320	80	40	0.96
Measuring tiles	10 sec/point	3320	160	120	1.00
Marking tiles	0.2 sec/cm	996	27	17	0.29
Setting tiles	4 sec/piece	664	16	8	0.19
Cutting tiles	1 sec/cm	4980	135	86	1.44
Storing tiles	10 sec/piece	1660	40	20	0.48
					4.36

Productive time for installing tiles

Task	Average productivity time per unit	Uncut tiles	One cut tiles	Two cuts tiles	Three cuts tiles	Productive time (hour)
Preparing adhesive	120 sec/m2					1.49
Spreading adhesive	300 sec/m2					3.73
Handling tiles	20 sec/piece	7900	3320	80	40	3.15
Positioning tiles	5 sec/piece		830	20	10	0.24
Setting tiles	55 sec/piece	21725	5856	86	83	7.71
						16.32
Average total productive labor time = 4.36 + 16.32 = 20.68 labor hours						20.68