Performance indicators for the reinforced concrete structures design: the Águas Claras case study.

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Abstract

A critical factor that determines the success of any continuous improvement process is the ability to quantitatively measure performance. But, it is difficult to understand, manage, or improve parameters that cannot be quantitatively measured; therefore, this paper presents performance indicators focused on material consumption for the building design of concrete structures. The indicators were applied to building projects provided by structural designers in Brasilia, Brazil and focused on the structural typology of buildings in the neighborhood of Águas Claras. To obtain the indicators, the buildings were grouped according to the structural solution adopted in the project to analyze the influence of the structural solution on the consumption of concrete and steel materials. Finally, the obtained values were compared with benchmark values from previous studies.

Keywords: product design; project management; performance measurement; concrete structures.

1 Introduction

When a structural design is required to meet certain performance standards, like in a target value design process (Ballard, 2011), the characteristic values of the design are compared with a benchmark database, and the values must fall within previously established ranges. This database may be composed of projects by the author of the analyzed project or by other authors.

Performance indicators are useful for comparing projects (Harbour, 2009). With these indicators, operational limits can be determined by defining confidence intervals for the selected indicator. Therefore, in addition to allowing a product to be compared with other quality products, indicators enable the production process in a given design to be internally monitored.

The use of performance evaluations in the construction industry has gained popularity as a research topic since the early 2000s, as shown in Lin and Shen's (2007) extensive literature review. However, only 4.5% of the studies cited in this literature review were dedicated to the design phase of the project (*design*). Studies regarding the measurement of performance in the design process (design as a service) and the assessment of information quality in the design documentation (design as a product) were included in this percentage.

Benchmarks for measuring the performance of design as either a service or a product in the construction industry are difficult to define due to the unique character assumed by each designed "building" (Bassioni, Price, & Hassan, 2004). Aspects such as shape (tall or low buildings), destination (residential, commercial, educational, industry, etc.), ownership (public or private) and location (urban or rural) cause different aspects of the building product to be emphasized, which directly impacts the design process, the evaluation of its performance, and the perception of its quality.

The following are examples of indicator systems and benchmark databases in the construction industry: the KPI Working Group (2000), the Indicator System of Brazil (NORIE, 2003), the National Benchmarking

System of Chile (CDT, 2001), the Construction Industry Institute Benchmarking and Metrics Program in the USA (CII, 1993), and the *Byggeriets Evaluerings* Center in Denmark (BEC, 2002). Detailed descriptions of these systems can be found in Costa, Horta, Guimarães, Cunha, Nóvoa, and Souza (2006). These indicator databases are less effective for small projects due to the profile of the indicators described above and the difficulty in classifying projects when defining benchmarks. Furthermore, the size of the databases are limited due to the small number of participating companies (Costa, Horta, Guimarães, Cunha, Nóvoa, & Sousa, 2006) and existing data are difficult to access for nonaffiliated companies and professionals.

As a result, the limited number of systems impairs the ability for comparing performance using other systems or benchmarks (Lam, Chan, & Chan, 2008). In a critique of performance evaluation systems available in the construction industry, Bassioni, Price, and Hassan (2004) and Lin and Shen (2007) noted that one of the shortcomings was the lack of measurements directed at the development process, i.e., design.

This introduction emphasizes the need to define simple, easy-to-use indicators to enable performance to be monitored and managed in small design projects.

2 Objective

This study aimed to define performance indicators for the design of concrete structures in residential buildings and focused on the consumption of three materials used in the designed structure: concrete, steel and formwork.

With these indicators, the benchmark set is defined with sample buildings located in the neighborhood of Águas Claras, Brasilia (Brazil), and the obtained values are compared with those from other databases in the literature.

In particular, this study classified the surveyed buildings according to the adopted structural solution and defined indicator ranges for each solution. Therefore, this study aimed to provide developers operating in the region with a tool for analyzing and monitoring their own projects, by comparing each new project's indicators with an indicators benchmark database.

3 Methodology

This study can be divided into four phases: problem definition and sample selection; database creation; identification of indicators; and data display and comparison with other databases.

3.1 Problem definition and sample selection

This study searched for design performance indicators that focused on the consumption of materials in concrete structures for residential buildings. Therefore, production aspects, such as execution speed, number of workers involved, and loss and reuse of materials, were not considered.

Reinforced concrete structures for tall, approximately 20-story residential buildings were analyzed according to the "tower" typology, which prioritizes height over horizontal dimensions, with the following structural solutions: beam and solid slab; beam and waffle slab; solid flat slab; and waffle flat slab (Bhatt, MacGinley, & Choo, 2006).

All buildings considered in this study use *in situ* concrete structure. In this kind of solution the structure is built on the building site using a type of boxing – formwork - into which the wet concrete is poured. The steel bars needed to reinforce the concrete are positioned within the formwork before the concrete is poured in. After the concrete gets the specified strength the formwork is removed.

Four kinds of floor structural solutions are considered in this paper:

- Beam and solid slab: all slabs have constant thickness and are supported in his outline by beams. Both the upper side and the underside of the slab are smooth surfaces (Figure 1);

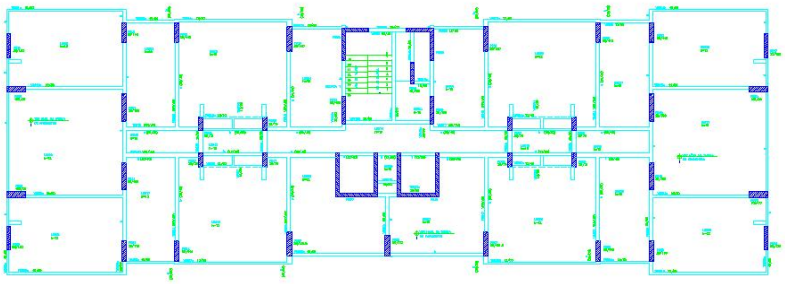

Figure 1: Beam and solid slab solution. Bottom view of concrete floor.

- Beam and waffle slab: all the slabs have ribs that run the length and width of the slab, generally several inches protruding from the lower surface of the slab. All slabs are supported by beams in outline (Figure 2);

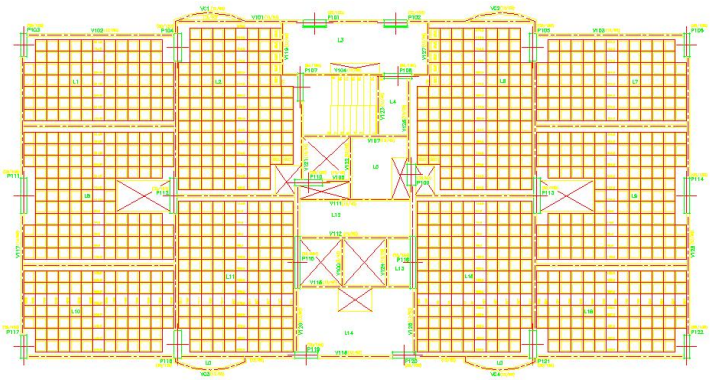

Figure 2: Beam and waffle slab solution. Bottom view of concrete floor.

- Solid flat slab: all slabs have constant thickness and are supported directly by the columns, with no beams (Figure 3);

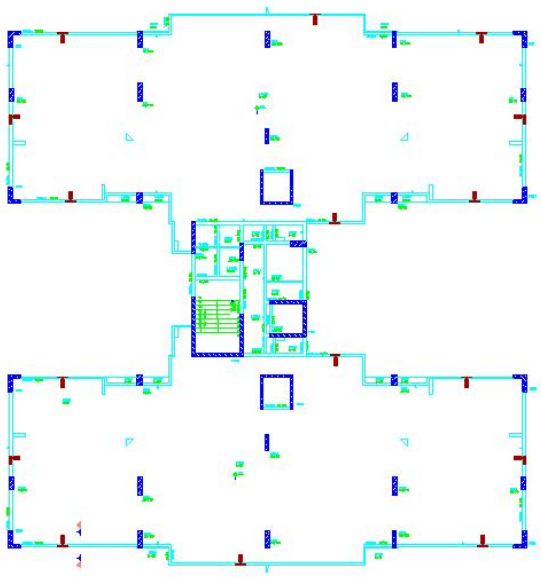

Figure 3: Solid flat slab solution. Bottom view of concrete floor.

- Waffle flat slabs: all the slabs have ribs that run the length and width of the slab, generally several inches protruding from the lower surface of the slab and are supported directly by the columns, with no beams (Figure 4);

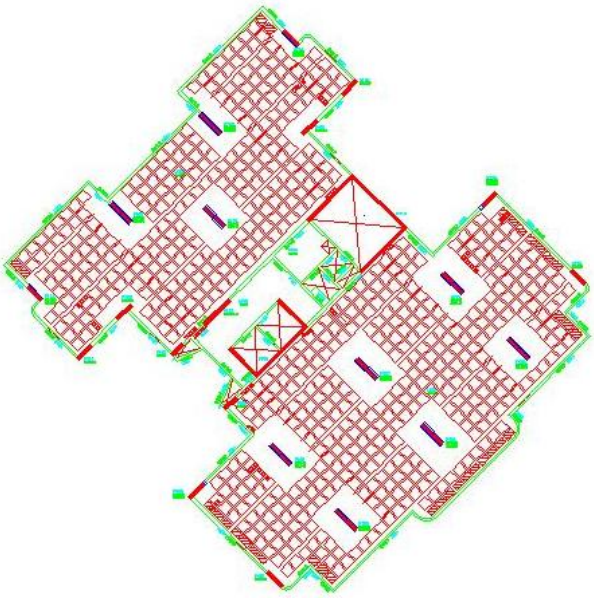

Figure 4: Waffle flat slab solution. Bottom view of concrete floor.

The neighborhood of Águas Claras in Brasilia (Brazil) was chosen as the study site because of the uniformity of its building typology and the temporal proximity in which the buildings were designed (2000-2003).

3.2 Database construction

The database was created with the structural designs of 30 buildings that met the typology described in Section 3.1 developed in five structural designers' offices in Brasilia. All the examined designs were developed according to Brazilian NBR 6118:1978 technical standard (ABNT, 1978).

Each building was catalogued in a database, and the number of floors, structural solution adopted, built-up area, concrete volume, and total steel weight were recorded. For future use, the quantities of each material were logged according to the floor and source of the structural element.

3.3 Determination of indicators

The selection of performance indicators for a particular design must focus on simplicity in terms of both the data collection and comparison with previously established databases.

Four indicators were adopted for each of the four main components in the cost composition of reinforced concrete structures (Oliveira, Lantelme, & Formoso, 1995) (Estefani & Sposto, 2002) (Soares, 2002).

- Relationship between the steel weight and built-up area (I_S): indicates the oversizing of the armor, especially on the pillars;
- Relationship between the concrete volume and built-up area (I_C): this indicates the oversizing of the slabs, beams, and pillars;
- Relationship between the formwork area and built-up area (I_F): this indicates the rationality of the design relative to the shapes; and

- Relationship between the steel weight and concrete volume ($I_{S/C}$): this allows for the preliminary assessment of the structure cost relative to the standard costs.

3.4 Data display and comparison with other databases

The indicators defined in Section 3.3 were calculated from the data gathered in the database described in Section 3.2 and were used to generated performance indicators (Harbour, 2009) for each building.

The buildings were grouped according to structural solution. The average value of each performance indicator weighted by the built-up area, standard deviation of the sample, and confidence interval were calculated for each group (Grant & Leavenworth, 1996).

The values obtained are displayed in terms of structural solution and performance indicator.

Finally, the process was repeated for the entire sample, with the global values of the performance indicators obtained for buildings with the "Águas Claras" typology.

The results obtained were compared with the values reported by Soares (2002) and the NORIE database (NORIE, 2003).

4 Results

4.1 Performance indicators for Águas Claras

For comparison purposes, the Figure 5 presents the relative average values of the buildings' performance indicators grouped according to the adopted structural solution.

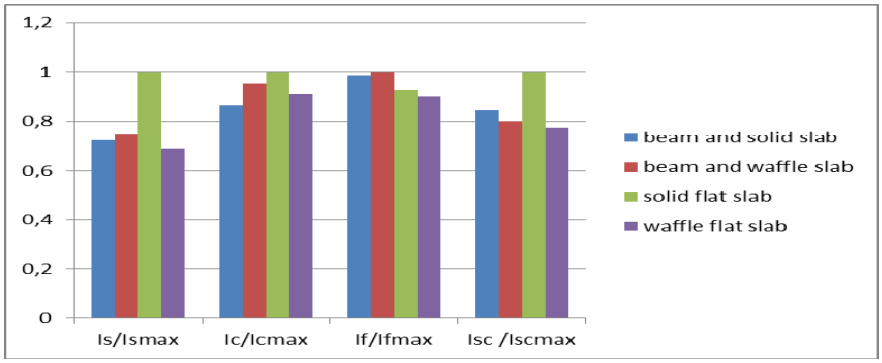

Figure 5: Relative average values of performance indicators ($I/I_{máx}$) grouped according the structural solution.

The average values and confidence intervals of each proposed indicator are shown according to the structural solution as follows are presented in Table 1.

Table 1: Average values and confidence intervals by structural solution.

	Is (kg/m2)			Ic (m3/m2)			If (m2/m2)			Is/c (kg/m3)		
Structural System	low	average	high	low	average	high	low	average	high	low	average	high
beam and solid slab	16,00	18,75	21,51	0,17	0,19	0,21	1,83	1,96	2,08	86,84	97,12	107,40
beam and waffle slab	14,25	19,36	24,48	0,19	0,21	0,24	1,86	1,99	2,13	65,16	91,86	118,55
solid flat slab	17,44	25,87	34,31	0,17	0,22	0,28	1,86	1,85	2,13	65,16	115,04	118,55
waffle flat slab	14,80	17,79	20,79	0,17	0,20	0,23	1,57	1,79	2,00	77,11	89,20	101,28

Finally, Table 2 shows the average values and confidence intervals of the indicators calculated for the entire sample.

Table 2: Global average values and confidence interval.

		Global		
		Low	Average	High
Is	(kg/m2)	17,62	19,59	21,55
Ic	(m3/m2)	0,19	0,2	0,21
If	(m2/m2)	1,76	1,87	1,97
Is/c	(kg/m3)	90,1	97,01	103,92

4.2 Comparison with other databases

To verify the proposed performance indicators, Table 3 shows the values obtained for the buildings in Águas Claras that used the beam and solid slab structural solution, followed by the corresponding values reported by NORIE (2003) and Soares (2002).

Table 3: Performance values from Águas Claras, NORIE (2003)) and Soares (2002).

		Águas Claras	NORIE	Soares
Is	(kg/m2)	18,75	13,84	11,36
Ic	(m3/m2)	0,19	0,17	0,21
If	(m2/m2)	1,96	1,94	1,97
Is/c	(kg/m3)	97,12	91,21	103,92

Before these values were analyzed, the following clarifications were considered: 1) the NORIE and Soares indicators only included buildings with beam and solid slab structural solutions; 2) the data compiled by NORIE were obtained for a group of buildings with different destinations, including residential and commercial buildings; and 3) the Soares study focused on buildings for military use that had a small number of floors.

Given the differences in the buildings examined in the three studies represented in Table 3, the analysis of the results should be limited to the qualitative variations in the obtained values instead of a direct comparison.

Thus, the following should be noted:

1. The NORIE values are within the range of the indicators calculated in this study, with the exception of I_A, which was below the lower confidence interval limit in the NORIE study. However, this result may reflect the different typology of the buildings in the NORIE area, where most of the buildings have fewer floors than the buildings in Águas Claras.
2. Regarding the comparison with Soares, the notably lower values correspond to the low number of floors in the studied buildings, which confirms the expected trend in the behavior of the indicators.

5 Conclusion

This study examined a set of performance indicators for concrete structures intended for tall residential buildings that are designed according to four different structural solutions. The proposed indicators were applied to buildings designed for the neighborhood of Águas Claras, and a database of performance indicators was generated for use as a benchmark for future projects.

The values shown in Figure 1 allow engineers to adopt a previous analysis of the solution accounting for the consumption of the three main components of the final structure cost: concrete, steel, and formwork.

Finally, the comparison of the values obtained in this study with values in databases available in the literature indicated that the adoption of the four proposed indicators is promising and should be further studied.

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