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A Study on the Use of Performance Indicators in Project Monitoring of Reinforced Concrete Structures Design

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Abstract
A critical factor that determines the success of any continuous improvement process is the ability to quantitatively measure performance. After all, it is difficult to understand, manage, or improve parameters that cannot be quantitatively measured; with the aim of providing concrete structure designers with a design performance monitoring tool, this paper presents performance indicators focused on material consumption for the building concrete structures design. The proposed indicators were applied to building projects provided by structural designers in Brasilia, Brazil, and focused on the structural typology of buildings in the Águas Claras neighborhood. To apply the performance indicators, the buildings were grouped according to the structural solution adopted in the project making possible to analyze the influence the structural solution has on the consumption of concrete and steel materials. Finally, the obtained values were compared with benchmark values from previous studies as well as with values from a building designed in accordance with a new version of the Brazilian concrete design technical standard. In the end, this paper improves the knowledge on the influence of design decisions on the consumption of raw materials in building concrete structures and it provides the structural designers with a tool set to monitoring their projects performance.

Key words: *concrete structures; performance measurement; product design; project management.*

1. INTRODUCTION

When a structural design is required to meet certain performance standards, selected characteristic values of the design are compared with a benchmark database and the values must fall within previously established ranges. The benchmark database may be composed of projects developed by the same author of the analyzed project or may be obtained from others developed by different designers. In the latter case the results can be used to analyse the performance of a project office in relation to the buildings' design market. In the first case though, the obtained result allows the designer to identify variations in the production process of the building design inside their own project office.

Performance indicators are a tool widely used for identifying and comparing characteristic values of products and process in the manufacturing industry. With these indicators, operational limits can be determined by defining confidence intervals for the selected indicator values, also named performance indices [1]. Therefore, in addition to allowing a product to be compared with other quality products, performance indicators enable the production process in a given design to be internally monitored.

Although the performance indicators are present in the processing industry since the second half of the last century, the performance evaluations in the construction industry have gained popularity as a research topic only in the early 2000's as shown by Lin and Shen [2] in an extensive literature review. However, only 4.5% of the studies cited in this literature review were dedicated to the design phase of the buildings project (design). Studies regarding the measurement of performance in the design process (design as a service) and the information quality assessment in the design documentation (design as a product) were included in this percentage. Also, a proposal of indicators to assess the performance of the buildings' design process - productivity, cost and lead time - can be found in Aquere [3], Aquere et al. [4] and Ezeldin and Abu-Ghazala [5].

Benchmarks for measuring the design performance as either a service or a product in the construction industry are difficult to define due to the unique characteristic assumed by each designed "building" [6]. Different aspects such as shape (tall or low buildings, tower or laminar typology, etc.), destination (residential, commercial, educational, industry, etc.), ownership (public or private) and location (urban or rural) directly impact the building 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 [7], the Indicator System of Brazil [8], the National Benchmarking System of Chile [8], the Construction Industry Institute Benchmarking and Metrics Program in the USA [10], and the Byggeriets Evaluerings Center in Denmark [11]. Detailed descriptions of these systems can be found in Costa et al [12]. However, these databases are not effective for small projects [13] due to the profile of the indicators described above and also because of their difficulty in classifying the projects when defining benchmarks [14, 15]. Furthermore, the size of the databases are limited as a result of the small number of participating companies [12] and existing data are difficult to access for non-affiliated companies and professionals [16].

Consequently, the limited number of systems impairs the ability to compare performance using other systems or benchmarks [17-19]. In a critique of performance evaluation systems available in the construction industry, Bassioni, Price and Hassan [6] and Lin and Shen [2] noted that one of the shortcomings was the lack of measurements directed at the buildings development process, i.e., buildings design.

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

2. OBJECTIVE

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

After defining a set of performance indicators, this study intends to build a database with performance indices from buildings designed in the region of Brasilia, Brazil.

In particular this study classifies the surveyed buildings according to the adopted structural solution and defined indicator ranges for each solution in order to make possible to analyse the influence of the structural solution on the raw materials consumption.

Above all, this research aims to provide developers operating in the region with a tool set for analyzing and monitoring their own projects by comparing each new project's indicators with an indicators benchmark database.

At the end, this paper improves the knowledge on the influence of design decisions on the consumption of raw materials in buildings concrete structures and it provides the structural designers community with a tool set to monitoring the performance of their projects.

3. METHODOLOGY

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

First of all, the performance measurement on concrete structures design is understood and the research field is defined. After the research field is made clear, a database is created with concrete structures designs obtained from design offices located in Brasilia region. All the designs have to be classified; the raw material quantities computed for each buildings design and the result put in a datasheet. This research focuses on concrete structures for residential buildings.

With focus on the raw materials consumption, the proposed performance indicators must be defined in a way that they could be easily calculated from the design documentation, making possible to compare two different building designs and estimate the final cost of the designed structure.

With these indicators, a benchmark set is defined with sample residential buildings located in the *Águas Claras* neighbourhood, Brasilia (Brazil), all of them designed following Brazilian NBR 6118:1978 technical standard [20] The obtained values are then compared with those from other benchmark databases found in the literature.

Finally, as a testing for future research, one of the buildings is redesigned according to the new NBR 6118: 2003 [21]. The indices of performance of this new project are then compared with the values previously obtained in an attempt to identify the impact of design changes imposed by the new standard.

4. WORK DEVELOPMENT

This chapter describes the work developed, as stated by the phases described in the Methodology.

4.1 Problem definition and sample selection

According to Harbour [1] a performance measurement process has to answer three questions:

- Why to measure?
- What to measure? And;
- How to measure?

Regarding the first question, a good reason for measuring performance is the fact that it helps the structural designer to: 1) choose the structural solution to be adopted in a given project; 2) previously estimate the final cost of the structure to be built; 3) validate the final design by comparing a given project results with a benchmark database formed by formerly designed buildings.

As for the question of "what to measure", this research focuses on the consumption of raw material in concrete structure: steel, concrete and formwork. As a general rule in the construction industry this study takes into account the weight of steel (kg), the volume of concrete (m^3) and the area of formwork (m^2) to compute the raw material consumption.

Finally, with the aim of helping the structural designer to compare material consumption between two or more buildings structures designs, four performance indicators are proposed in Section 5.1.

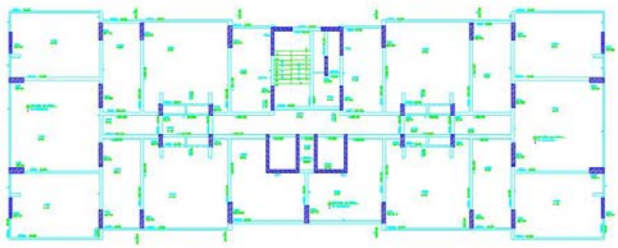

Figure 1. Beam and solid slab solution. Bottom view of the concrete floor

It is important to point out that this study searches for design performance indicators that focus on the consumption of materials in concrete structures for residential buildings as specified in the design documentation. Therefore, production aspects such as execution speed, number of workers involved and loss and reuse of materials are not considered.

Although the performance indicators proposed are valid for any type of reinforced concrete structures, bridges for example, in this paper only reinforced concrete structures for tall – approximately 20-story – residential buildings were analyzed. All the analyzed buildings are in accord with the "tower" typology, which prioritizes height over horizontal dimensions. To apply the proposed indicators the selected buildings are grouped in four structural solutions which are: beam and solid slab; beam and waffle slab; solid flat slab; and waffle flat slab [22].

The four kinds of floor structural solutions considered in this paper:

- *Beam and solid slab:* all slabs have constant thickness and are supported in its outline by beams. Both the upper side and the underside of the slab are smooth surfaces (Fig. 1);
- *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 (Fig. 2);

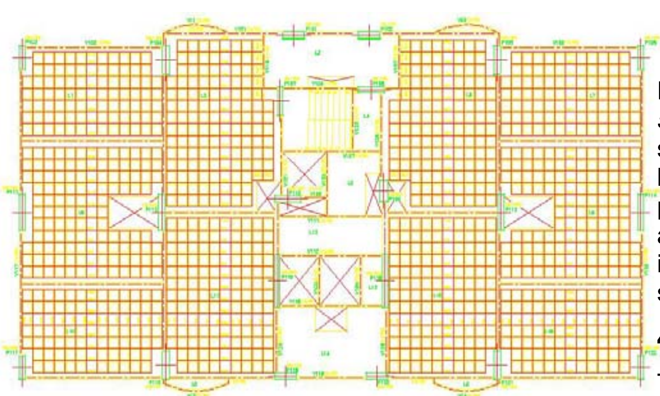

Figure 2. Beam and waffle slab solution. Bottom view of the concrete floor.

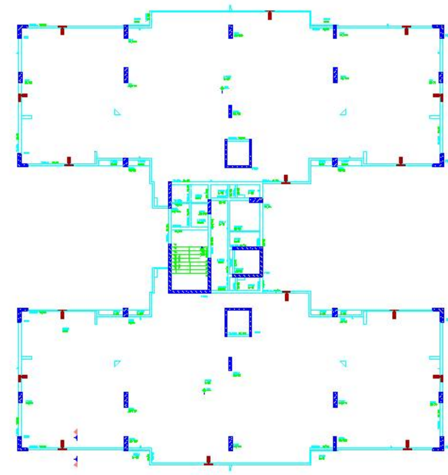

Figure 3. Solid flat slab solution. Bottom view of the concrete floor.

- *Solid flat slab: all slabs have constant thickness and are supported directly by the columns, with no beams (Fig. 3);*
- *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 (Fig. 4);

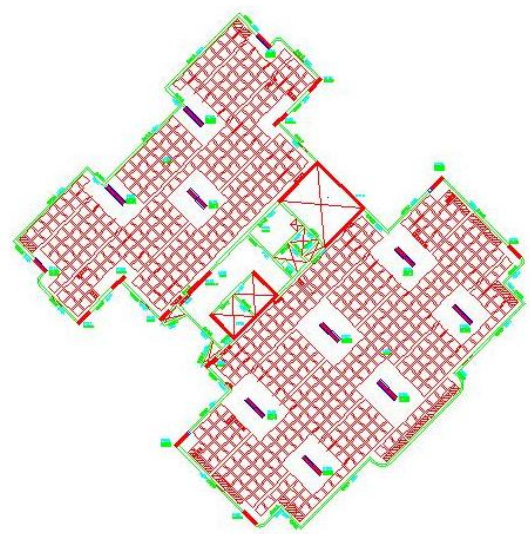

Figure 4. Waffle flat slab solution. Bottom view of the concrete floor.

Finally, all the 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.

4.2 *Database Construction*

The database was created with 30 buildings structural designs from five structural design offices in Brasilia that had met the typology described in Section 4.1. All the examined designs were developed in compliance with Brazilian NBR 6118:1978 technical standard [20].

The *Águas Claras* neighborhood 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). 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. A list of all data organized by buildings can be found in Cruz [23].

4.3 *Determining 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 [24 - 26].

- Relationship between the steel weight and built-up area (I_S), (Eq. 1) indicating the armor oversizing, especially on the pillars:

$$I_S = \frac{Steel\ weight}{built\text{-}up\ area\ according\ NBR-12721} \quad (1)$$

- Relationship between the concrete volume and built-up area (I_C), (Eq. 2) indicating the oversizing of the slabs, beams, and pillars;

$$I_C = \frac{Concrete\ volume}{built\text{-}up\ area\ according\ NBR-12721} \quad (2)$$

- Relationship between the formwork area and built-up area (I_F), (Eq. 3) indicating the rationality of the design relative to the shapes and the speed of construction, or structural buildability [27]:

$$I_F = \frac{Formwork\ area}{built\text{-}up\ area\ according\ NBR-12721} \quad (3)$$

- Relationship between the steel weight and concrete volume ($I_{S/c}$), (Eq. 4) allowing the preliminary assessment of the structure cost relative to the standard costs:

$$I_{S/C} = \frac{Steel\ weight}{Concrete\ volume} \quad (4)$$

When calculating the proposed indicators, the weight of steel and the concrete volume of foundation elements are not computed. Such decision was made in order to eliminate the influence that the soil type on which the building is constructed has on the final values obtained for the indicators. Still, the building area is calculated in conformity with the item 3.7.1.4 of NBR-12721: 2005 [28]. In this case, the built-up area is defined as the sum of the covered and uncovered real areas of all floors in the building, calculated from the architectural design documentation.

All the data necessary to compute the proposed indicators – steel weight, concrete volume and formwork area – are automatically displayed by concrete structure design software.

4.4 *Data display and comparison with other databases*

First of all, the Performance indices [1] for each building are generated by using the indicators defined in Section 4.3 and the data are gathered in the database described in Section 4.2.

After that, the buildings are grouped according to structural solution as specified in Section 4.1. The average value of each performance indices weighted by the built-up area, standard deviation of the sample and confidence interval were calculated for each group [29]. The values obtained are then displayed in terms of structural solution and performance indicator.

Finally, the performance indices computation process is repeated for the entire sample resulting in global values of the performance indicators for buildings with the *Águas Claras* typology.

However, the values obtained from the performance indicators - or performance indices [1] - are not useful unless they can be compared with ones from the bibliography or obtained from other companies [30]. So, with the purpose of verifying the proposed performance indicators, two references from the bibliography review are used as a benchmark: The NORIE database [8] and Soares's work [26].

The NORIE's database is maintained by the University of Rio Grande do Sul (Brazil) and was formed by the contributions of almost 200 companies from the construction industry field in Brazil. Unlike the present research, NORIE's database is composed by both residential and commercial buildings with a small number of floors, and the buildings typology is not registered. Notwithstanding, all the buildings in the NORIE's database use the beam and solid slab structural solution.

The Soares's work, on the other hand, considers only military buildings with a small number of floors and laminar typology which prioritizes horizontal dimensions over height. As in NORIE, all the buildings in Soares's research use the beam and solid slab structural solution.

The decision on using NORIE [8] and Soares [26] as benchmarks take into account that just as *Águas Claras*, all the buildings in both researches were constructed in Brazil, all of them were built in the last two decades of the twentieth century according to the NBR 6118:1978 [20] technical standards and all of them used *in situ* reinforced concrete structures.

So, as a validation test, the performance indices for the beam and solid slabs structural solution from *Águas Claras* typology are compared with the performance indices values reported by Soares [26] and by the NORIE's database [8].

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

Structural Solution	I_s (kg/m^2)			I_c (m^3/m^2)			I_f (m^2/m^3)			$I_{s/c}$ (kg/m^3)		
	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	107,4
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	1,58	1,85	2,11	105,99	115,04	124,09
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

5. RESULTS

5.1 Performance indices for Águas Claras

The results for the performance indicators applied to buildings with *Águas Claras* typology are now presented on a set of one figure and three tables organized in a way to help structural designers make decisions along the building design process.

First of all, in order to allow comparison between the four structural solutions adopted in this research, the Fig. 1 presents the relative average values of the buildings' performance indicators grouped conforming to the adopted structural solution.

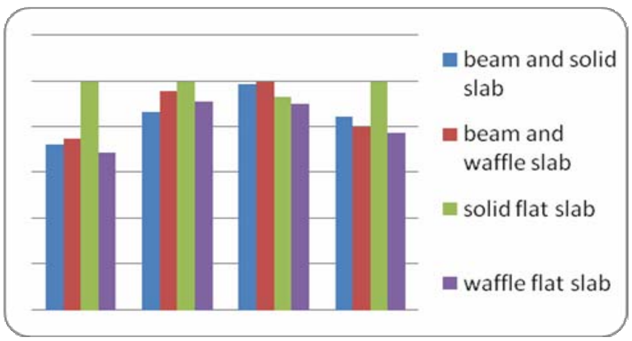

Figure 1. Relative average values of performance indicators (I/Imax) grouped according to the structural solution.

The information in Figure 1 can help the structural designer decide which structural solution will be adopted pursuant to the parameter that is most important at the moment. If the priority is to reduce the steel consumption – for example, in times when the steel price is very high – the choice should be the waffle flat slab solution which presents the lower I_S. However, if the priority is low consumption of concrete, the beam and solid slab solution is most likely the best option. Finally, Figure 1 shows that the solid flat slab solution and the waffle flat slab solution present the lowest I_f indices. Since the formwork area is related to construction time, these solutions are the best ones if the lead time is the top priority.

From the Figure 1 it is possible to verify that the waffle flat slab presents the lowest values for all indicators, which is coherent with the popularity of this solution among the structural designers.

As a second tool, Table 1 presents the average values and confidence intervals of each proposed indicator grouped in agreement with the structural solution.

By using the mean values shown in Table 1 and the values of unit cost [31] for each of the three inputs - steel, concrete and formwork - it is possible to obtain an estimation of the cost per square meter of the structure to be designed. Finally, with the built-up area from the architectural design documentation we obtain an estimation of the cost of the structure to be built.

In order to have an overview of the indicators applied to buildings with the typology *Águas Claras*, Table 2 shows the average values and confidence intervals of the indicators calculated for the entire sample. These global average values can be used to help decision making on starting a new building project on *Águas Claras* neighborhood.

Table 2. Global average values and confidence interval.

Indicator	Global		
	low	average	high
I_s (kg/m^2)	17,62	19,59	21,55
I_c (m^3/m^2)	0,19	0,20	0,21
I_f (m^2/m^3)	1,76	1,87	1,97
$I_{s/c}$ (kg/m^3)	90,01	97,01	103,92

With this set of tools at hand, the structural designer can previously estimate the cost of the structure to be built and decide which solution to adopt. Also, the performance indices presented in Table 1 and Table 2, used as benchmark, allow the structural designer to execute a final validation of their design after the design process is finished.

5.2 *Comparison with other databases*

To verify the proposed performance indicators, Table 3 shows the values obtained for the buildings in *Águas Claras* that use the beam and solid slab structural solution, followed by the corresponding values reported by NORIE [8] and Soares [26].

Table 3. Performance values from *Águas Claras*, NORIE [8] and Soares [26].

Indicator	Águas Claras	NORIE	Soares
I_s (kg/m^2)	18,75	13,84	11,36
I_c (m^3/m^2)	0,19	0,17	0,14
I_f (m^2/m^3)	1,96	1,94	1,67
$I_{s/c}$ (kg/m^3)	97,12	91,21	83,31

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_S, which was below the lowest confidence interval limit in the NORIE and Soares studies. However, this result reflects the different typology of the buildings in the NORIE and Soares's database in which most of the buildings have fewer floors than the buildings in *Águas*

Claras. This difference is caused by the influence of the columns in the global indices: the greater the number of floors, more steel is required for the columns and therefore higher the I_S will be;

2. Regarding the comparison with Soares, the notably lower values correspond to the low number of floors – one and two floors buildings - in the studied buildings, which confirms the expected trend in the indicators' behavior;
3. Looking at the values in Table 3 as a whole, it is noted that the greatest differences occur in indicators I_S and $I_{S/C}$, just those with higher influence of the pillars, and thus the number of floors. Still, the variation in the values of the indices is proportional to the variation of the number of floors, being smaller in relation to NORIE [8] and higher compared to Soares [26]. Finally, the values associated with the indicators I_c and I_F - which depend mainly on the structural solution adopted in each floor – have variances below 10%.

5.3 *Comparing technical standars*

Since 2003 the design of a concrete structure for buildings in Brazil has to be done in accordance with a new version of the NBR 6118 technical standard, designed as NBR 6118:2003 [21]. This new technical standard introduces new mandatory demands for the concrete structure design - such as vibration analysis of slabs - as well as modifies previously adopted minimum values for the dimensions of structural parts and for the reinforcement ratio.

As a test of the ability of the proposed performance parameters to detect variations on the consumption of raw materials due the technical standard changes, one of the buildings previously analyzed was redesigned according to new NBR 6118:2003. All design parameters except those modified by the new technical standard were kept the same. The adopted structural solution was the beam and solid slab structural one.

After that, the performance indices for the redesigned building were calculated and compared with those from the first line of Table 1. The results are shown in Table 4.

They show an increase of the formwork area (I_F) and of the reinforcement ratio ($I_{S/C}$). The steel consumption (I_S) and concrete consumption (I_C) are lower than that in 1978.

However, all the performance indices are in the confidence interval shown in Table 1, which shows that the present database size is still not enough to guarantee the necessary precision to capture the performance indices variations due to the new standard modifications.

Table 4: Performance values: NBR 6118:1978 [20], NBR 6118:2003 [21] and variation.

Indicator	Beam and solid slab		
	1978	2003	Variation (%)
I_s (kg/m^2)	18,75	18,46	-1,55
I_c (m^3/m^2)	0,19	0,18	-5,26
I_f (m^2/m^3)	1,96	2,13	8,78
$I_{s/c}$ (kg/m^3)	97,12	101,57	4,58

6. 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 then applied to buildings designed for *Águas Claras* neighborhood (Brazil), and a database of performance indices was generated to be used as a benchmark for future projects.

The resulting indices were organized in a set of figures and tables in order to allow structural designers to evaluate the best structural solution for each building design taking into consideration the consumption of the three main components of the final structure cost: concrete, steel, and formwork.

From the resulting relative indices, shown on Figure 1, it is possible to verify, for example, that the waffle flat slab solution is the one with lowest material consumption – represented by lowest I_s and I_c – as well as the one with better buildability represented by the lowest I_F. These results make the waffle flat slab the structural solution most suited for occasions when the steel prices are high and the construction time is a critical factor to the success of the business.

Naturally the final decision on which structural solution is the most suited for each building design must take in account other parameters rather than just the consumption of raw materials.

Also, by using the average performance indices presented in Table 1 together with the unit construction prices found on technical publications, the structural designer can previously estimate the final cost of the concrete structure to be designed, according to the structural solution adopted.

Finally, a benchmark database created from previous projects is a powerful tool to be used on the quality control during the building design process as well as at the evaluation of the resulting structural design.

This work also shows the importance of defining the typology of the building when creating a benchmark database for performance indicators. The Table 2 shows results from three different databases, each one formed from different buildings typologies. Although the values shown in that table present a trend that is coherent with the database composition, they show the differences on indices values when the buildings typologies are not the same.

When trying to use the obtained performance indices to analyze the influence of the new technical structural demands on the material consumption, the results were not conclusive. It has become clear that the number of buildings in the existent database is too low and therefore the confidence intervals are not suited for this kind of analyses.

However, 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.

As a target for future researches we consider: 1) applying the proposed performance indicators for isolated structural components – like beams, slabs, columns, stairs, etc. – in order to make possible to analyze the influence of each structural component on the raw material consumption; 2) studying new parameters to group the buildings instead of by typology; and 3) automating the extraction of the performance indicators from the design documentation and optimizing the interface of the existing database.

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Studija o upotrebi indikatora performansi u projektnom monitoringu projektovanja armirano-betonskih konstrukcija

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Rezime

Kritičan faktor koji određuje uspeh bilo kog kontinualnog procesa napretka jeste sposobnost da se kvantitativno izmere performanse. Na kraju krajeva, teško je razumeti, rukovoditi ili poboljšati parametre koji ne mogu da se kvantitativno izmere; u cilju da obezbedi betonsku konstrukciju, projektantima koji koriste dizajnerski alat, ovaj rad predstavlja indikatore performanse koji su fokusirani na korišćenje materijala za građenje betonskih konstrukcija. Predloženi indikatori su primenjeni na građevinske konstrukcije koje su obezbedili građevinski inženjeri niskogradnje u Braziliji, u Brazilu, i fokusiraće se na konstrukcijsku tipologiju zgrada u okruženju Agvas Klaras. Da bi primenile indikatore performansi, zgrade su grupisane prema konstrukcijskom rešenju usvojenom tokom izrade projekta i na taj način može da se analizira uticaj koji konstrukcijsko rešenje ima na utrošen betonski i čelični materijal. Konačno, dobijene vrednosti su upoređene sa benčmark vrednostima iz prethodnih studija, kao i sa vrednostima sa zgrade projektovane u skladu sa novom verzijom brazilskog tehničkog standarda za beton. Na kraju, ovaj rad poboljšava znanje o uticajima projektantnih odluka na utrošak sirovina u betonskim konstrukcijama i obezbeđuje inženjerima niskogradnje alat koji je namešten da posmatra njihove performanse projekta.

Ključne reči: *betonske konstrukcije; merenje performansi; projektovanje proizvoda; projektni menadžment*