EAAE – ARCC INTERNATIONAL CONFERENCE
June, 10-13,2020 | Valencia
Doi: http://dx.doi.org/10.4995/EAAE-ARCC-IC-2020.2020.XXXX

Constructability criterion for structural optimization in BIM and Hybrid Digital Twins

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ABSTRACT: The introduction of Lean Construction standards into the AEC Industry has changed the way that the professional approach the different problems. BIM and Hybrid Digital Twins are new high demanded technologies that improve the efficiency of the industry's procedures as they allow new and faster methodologies. Optimization algorithms are often used in combination with these techniques to improve the result at several points of the design phase, including the structural project. The optimization can be done using different criteria, like the economy, sustainability, energy consumption or constructability or a combination among them. While there exist exact formulas to quantify some of these criteria there is not a universal one to quantify the constructability. In this article, we establish the key points to create a constructability criterion for each structural project and explore its efficiency. The way to quantify the constructability depends on the structural design and element to be optimized and as there is not an exact formula to quantify the different factors that influence it have been defined and their combinations explored for a certain structural problem: optimization of a concrete beam. With this, we are able to quantify the easiness to build a certain structural project and reduce the building time and crew cost and create a way to improve the structural design. This exposed method can then be expanded to different structural elements.

KEYWORDS: BIM, Digital Twins, Constructability, Optimization Algorithms

INTRODUCTION

The Architecture, Engineering and Construction Industry (AEC Industry) has been one of the most static industries in the world and has been reluctant to changes, in the last years this tendency is starting to change. The introduction of powerful informatic tools creates a new environment where automatized tools can be developed for several tasks (Eastman et al. 2011). These tools allow the professionals to improve their productivity and quality of the project and at the same time have more control over it and are based upon management improvements.

Some of the management improvements to the industry are led by the increase in the usage of Building Information Modelling (BIM) Environments (Volk, Stengel, y Schultmann 2014) and Digital Twins (Chinesta et al. 2019). Both provide great advantages for the professionals as they are able to handle a lot of parameters and work with them simultaneously. Allowing the AEC Industry to introduce the different Lean Construction (LC) precepts effectively and improve the sustainability of the project. The adoption of the two different environments is an evolution to traditional methodologies and by using them the professionals are able to reduce the risk of errors during the project, achieve better accuracy through the design phase or their management capabilities. There is also utility when working in cloud-based servers (Jiao et al. 2013) with several people operating at the same time in the same model with coordinated modifications and improvements which are natural in both of them.

There are a lot of differences among both of the previously stated environments. On one side, BIM is hard to define term as it includes three concepts: a product, the digital file where the model of the project is stored, the specific type of software and the methodology used to create the model (Eastman et al. 2011) («Frequently Asked Questions About the National BIM Standard-United States™ | National BIM Standard - United States» 2016). BIM, in reality, is a mix between the three concepts is an n-dimensional matrix of the project's data where the user can define and relate new dimensions and variables between them, this set of dimensions is the digital model of the project that is developed on a BIM software and to properly use it the methodology has to be used. On the other side, Digital Twins are one step ahead of the BIM environments in terms of project management. They do not only work during the design phase but also during the life cycle of the building. A Digital Twin is a virtual model for a certain procedure, product or service which is continuously being updated with new input from the real object on the world. For the AEC Industry, it consists of a digital model of the building itself which is being updated through sensors from the building. This model can be used to visualize, analyze, simulate and plan everything on the building (Chinesta et al. 2019).

As seen each one of them has its advantages and its uses. BIM works better in the design and construction phase allowing the professionals to optimize results and procedures and Digital Twins are better managing variations and modifications through the life cycle of the building.

The environments by themselves are only a framework to control the project and visualize its different aspects simultaneously. They are a completely new methodology that is starting to change the way that the AEC is working. But by themselves, they are only able to control, show and manage parameters. To fully take advantage of the environments these parameters have to be analyzed in conjunction with each other. For this purpose, the Building Performance Tools (BPS Tools) are used, as they are able to take the parameters stored in the digital environments and use them for several tasks. A lot of BPS Tools have been developed through the last ten years to improve sustainability (Chong, Lee, y Wang 2017) (Lu et al. 2017), reduce CO_2 emissions (Chen y Luo 2014), waste reduction (Akinade et al. 2015), optimize structural design (Fernández-Mora y Yepes 2017), among other purposes.

A large group pf BPS Tools are focused on the design aspect of the project, helping the professionals to make decisions or even designing some elements by themselves, like structural elements. These design tools are based upon design restrictions (structural analysis and requirements) and design criteria like economy, sustainability, energy consumption or others. These design restrictions or directives can also be introduced into an optimization algorithm that is able to find an optimal design for the problem. In (Diao, Kato, y Hiyama 2011) we can find an example that uses a BPS Tool to optimize the CO_2 emissions for structural design.

One of these criteria that can influence the design of a structural element and improve it is the constructability. The constructability or buildability of a certain structural element measures its aptitude to be built. So, it is a measure of the easiness to build a certain element. Lower constructability measurements allow easier structures to be built and easier structures are more economical. It also reduces the number of mistakes occurring during the execution, because error appearance is directly related to the complexity of the element (Shrivastava, Chaurasia, y Saxena 2017).

The term constructability is usually referred to several aspects at the same time. First, the extent to which the design parameters facilitate the construction of the element while achieving the building requirements. Second, the effective and time integration of construction knowledge into the conceptual planning and field operations. Third, to balance the different environmental constraints, project goals and building performance. It is not an universally measurable criteria as different factor interact in a different way for each case.

In this paper, we aim to define a way to measure the constructability of an element and be able to compare it among other similar ones. This mathematical model to measure the constructability can then be used in a multicriteria optimization algorithm complementing other criteria and help the professionals to achieve an overall better design.

METHODOLOGY

Case Study

Per the definition above, the constructability is a criterion that has to be defined for each specific problem. So, in this problem, we will not find a universal definition to measure it, but a methodology to define it for every structural case, which will need further study.

In this paper, the case study is a concrete beam with rebars on both faces and transversal reinforcement. We use a fixed span of five meters and loads according to residential use, without any particularity that may alter the design there are constraints for both, bending and movements at each ending.

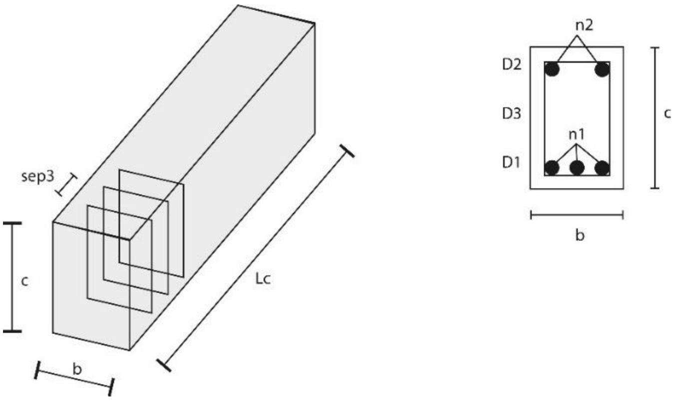

Figure 1 Geometrical parameters of a concrete beam

We assume that when measuring the constructability the design has been already validated and it is enough to resist the efforts on the beam. The constructability criteria will not check any design restriction, including those regarding the buildability itself as rebar disposition, assuming that they are sufficient for their structural requirements.

Parameter Definition

Fig. 1 contains the geometrical parameters of the beam. Its dimension is defined by two parameters, width (w) and height (h), in combination with the fixed span they define the external dimensions of the element. The distance between the face of the element and the rebar is defined by the cover (c) parameter. To define the rebar a total of six parameters have been used, three for the diameter of the different rebars: one for the diameter of the rebar in the bottom side of the beam (D1), a second for the diameter of the rebar in the top side (D2) and a third one (D3) for the transversal rebar. And three more to determine the number for each of the reinforcements: bottom rebar (n1), top rebar (n2) and the distance between the transversal rebars (sep3).

Constructability is not only related to the geometrical definition of the beam, but there are also other factors that can affect it. The weight of the different materials has to be taken into account through its density with two more parameters also the relationship with the other elements in contact and if it is needed the formwork and its size. The consistency of the concrete is another factor directly related. On-site or precast construction can also be a key factor because the parameters interact differently between them. Or the homogeneity of the rebar reinforcement understood as the use of rebars of similar sizes.

There are also factors external to the element itself such as the experience of the working crew, time of the day or weather that can affect the constructability of the element. In this paper, this is not taken into account, as our goal is to create a mathematical model able to handle the criteria for further use in the design stage. These parameters can’t be known prior to the execution and are independent of design changes and they can introduce noise in the model that will not improve it as they are nor design dependants.

Table of parameters	
Parameter	Measurement
Geometrical parameters	
Width (w)	Centimeters
Height (h)	Centimeters
Cover (c)	Centimeters
Bottom-side diameter (D1)	Millimeters
Top-side diameter (D2)	Milimeters
Transversal diameter (D3)	Millimeters
Number of bars in the bottom (n1)	Direct amount
Number of bars in the top (n2)	Direct amount
Spacing between transversal bars (sep3)	Centimeters

Non-geometrical parameters	
Concrete density	Kilonewton per cubic meter
Steel density	Kilonewton per cubic meter
Concrete consistency	Slump test
Rebar homogeneity	Mean value of the rebar diameter
Type of beam	h equal/greater than span thickness
Formwork	Square meters
Type of construction	On-site/Precast

Table 1 Parameters defining the case study

A total of 16 parameters have been used to define the constructability of a beam. Table 1 summarizes the different parameters and the units utilized to measure them. Some parameters are not measurable and describe certain characteristics of the element. To be able to compare and combine the factors into one criterion it is necessary to unify and categorize them. For this, a survey has been conducted among several AEC professionals, including architects, engineers and constructors asking for a hierarchy among the parameters.

RESULTS

Survey Results

The survey asked different professionals to sort the parameters in order of relevance for the constructability of a beam. With this approach, we can create a hierarchy for the parameters and determine their importance. The results of the survey are shown in Figures 1 and 2. The first one shows box-plots of the results showing the dispersion in the importance of the parameter for the different professionals. The second shows the mean value for each variable to show a tendency in their importance.

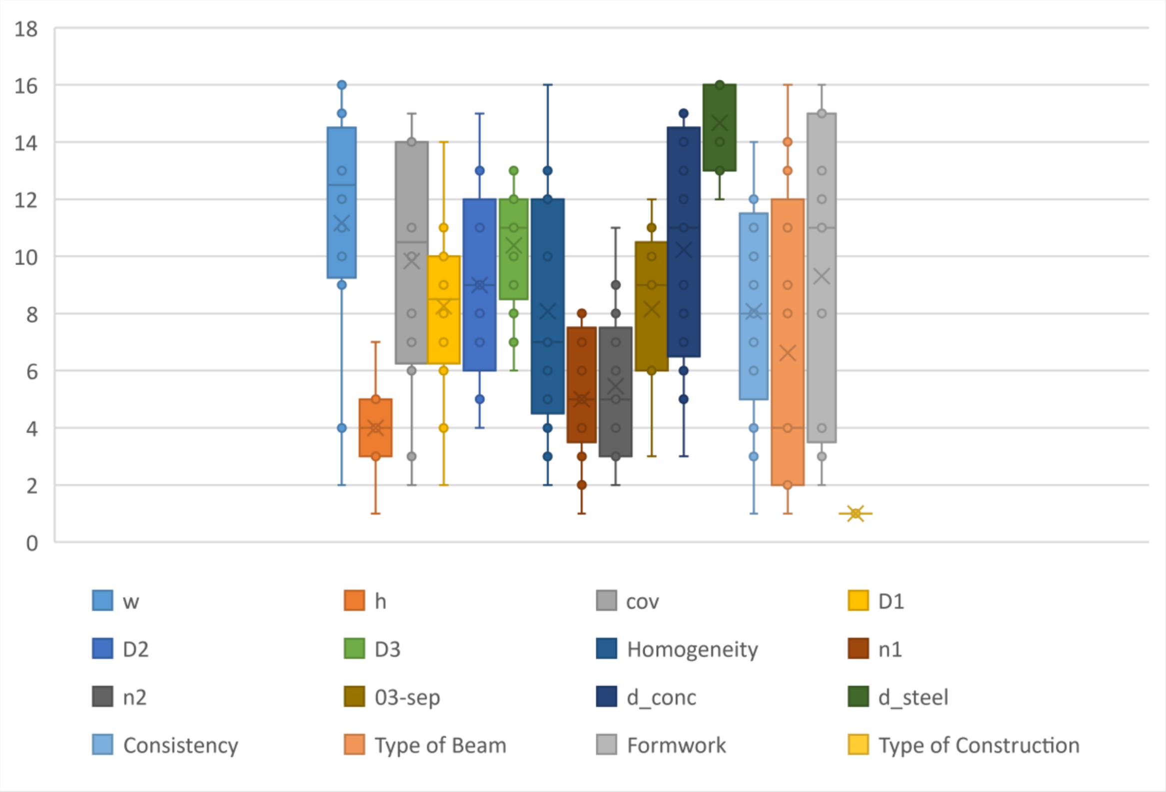

Figure 2 Box-plot diagram with the results of the survey

The box-plot diagram shows the dispersion in the results. The two parameters with lower mean, height, and type of construction, are also the parameters with less dispersion. Different unrelated professionals have agreed that these factors are the ones with a bigger influence on the constructability, as will be discussed with further detail later. The rest of the parameters have a bigger dispersion, which clearly indicates the problematic of the constructability, as it a very subjective measure and different professionals tend to prioritize different variables when designing the structural elements, this dispersion has to be taken into account to weigh the importance of each parameter.

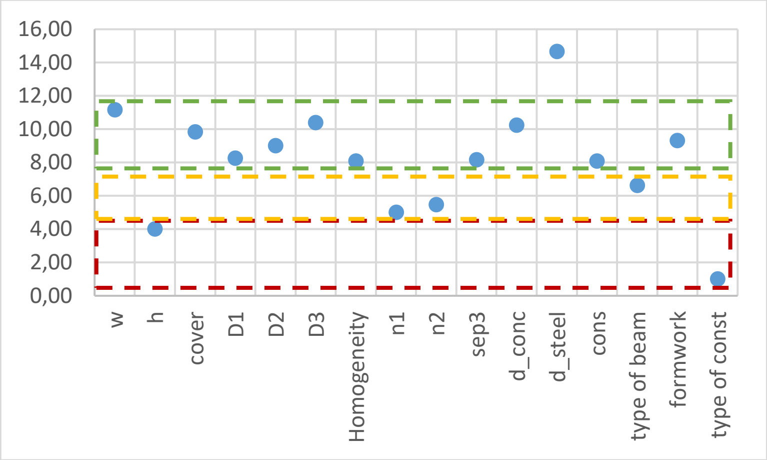

Figure 3 Mean value for each parameter

From Figure 2 we can gather the parameters into three different main groups regarding the importance. These clusters have been shown in the figure with the colored lines. The first group consists of two parameters, height and type of construction, both of them are related to the relationship of the beam with their environment, their mean values oscillate between one and four. The second group contains all the parameters regarding both rebars and type of beam. The third and last group covers the rest of the parameters, these group also has the biggest deviations in the box-plot diagram, so different professionals give different attention to them.

During the survey, the professionals were also asked about other parameters that were not taken into account in the research. Some of the professionals suggested the size of the arid as a parameter to be added. After further study, this has been discarded, as its effects are taken into account considering the number of rebars and the consistency of the concrete. There is also the fact that in some areas the size of the arid is determined by the availability and not chosen by the professional, so it can be considered an external factor instead of a parameter.

Hierarchy for constructability

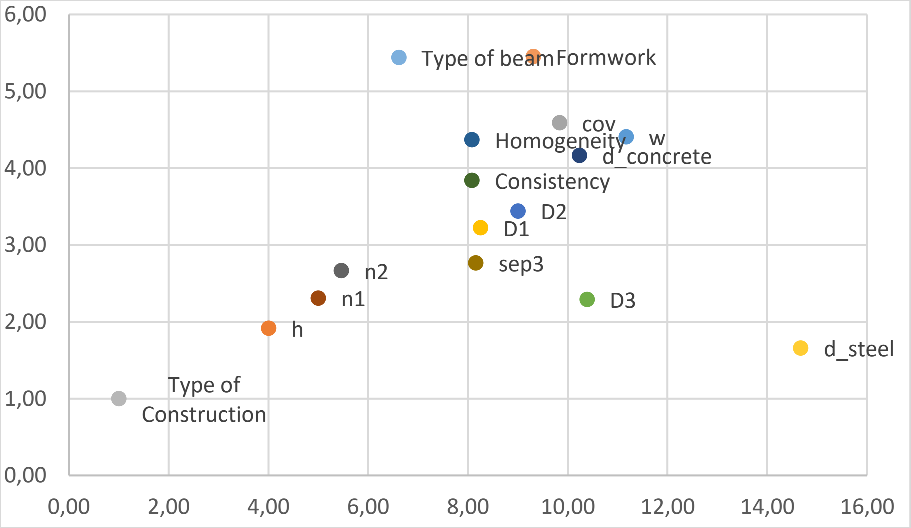

Figure 4 Cluster analysis of the mean and standard deviation for each parameter

From this survey, we can extract a hierarchy based upon the experience of the professionals and how they evaluate the constructability in a concrete beam and then establish a way to measure it. Figure 3 shows the correspondence between the mean value and the standard deviation for each parameter. A parameter with lower mean has been given more importance by the respondents and a lower standard deviation implies more agreement among the professionals in the importance of a certain parameter.

From the figure, we can see a tendency between the mean and the deviation, parameters with more importance are also important for most of the interviewees in almost a linear regression. This phenomenon is more accused in the first group of parameters and defines two sets of clusters encircled in the figure, there is a parameter outside of this phenomenon "steel density" which has been considered by most of professionals as the least valuable one. The parameter which has been given more importance is the "type of construction".

The first cluster is the one with higher importance and it will be considered in that way when considering the constructability analysis, either way, the second cluster is also relevant and influential even if it has less impact on the criterion. The "steel density" parameter has been unfavored by most of the professionals given its position, for this reason, we are going to discard it as its influence can be explained through other parameters that have a bigger impact on the whole environment. The "type of construction" parameter has been proved to have a lot of influence on the constructability and after analyzing the data its two values cannot be compared between them, so it is going to be considered as an external factor to achieve a more accurate result.

DISCUSSION

Units of measurement

After sorting the parameters and weighing them we are in need to establish a measurement system. Typically, an optimization criterion can be quantified using a certain unit, like currency when studying the economic aspect, the mass of carbon dioxide emitted during production or watts consumed among others for sustainability, but this cannot be done with the constructability as different units are taken into account. When assessing the constructability every parameter has its own unit and some of them are discrete variables dependent on the amount of something, like rebars placed. These quantifications cannot be mixed in a direct way as it will create inconsistency in the measurement.

There are two possibilities to unify the parameters in an indirect way: currency value and working time, both related to the efficiency of the working crew. Both of them can assess constructability in an indirect way. The economic value is usually also taken into account when using a multicriteria optimization algorithm, but it is hard to completely take into account the prize for the working crew exactly as can overload the computer with data or create inaccuracies due to too many factors taken into account. Other possibilities based on discrete quantitative indirect approaches can be used to evaluate the constructability as working crew time but it is hard to define.

Quantifying the constructability

From the survey results and the cluster analysis, we can confirm that there are factors which influence more than others The hierarchy shows which of them need more weight than the rest, we can also estimate that the first cluster is roughly twice as important as the second, because their total mean values differ in that proportion.

Optimization algorithms tend to overload the computer creating a huge population that must be handled and analyzed at the same time. Computational time is a determining factor in them and adjusting the methodology to evaluate the criteria is crucial. Depending on the research it is possible that it is beneficial to reduce the accuracy to favor the computational time. Through this paper, we have seen that constructability is not universal, either by the perception of the professionals or the units that can be measured. We are going to define several methods to quantify the constructability in a concrete beam, allowing us to adjust the computational cost to the necessities. The different proposed methods are sorted from lower to higher computational cost and data needed to perform the analysis.

-Number of rebar reinforcements:

The most influential parameters in the constructability are the rebars. The raw number of them is directly related to its constructability. An element with more rebars will need a bigger resource investment to be built as it gains complexity. So, the element with fewer rebars has more constructability than the rest. This criterion can be exposed by the following formula:

$$C_1 = n1 + n2 + \frac{sep3}{l}$$

-Number of rebar reinforcements modified:

Considering not only the rebar number but the difference in diameter among them creating and adding the height of the element into the criteria a more accurate scale can be obtained. This takes into account all the parameters existent in the first cluster and weighs them based upon its importance. The formula is the following:

$$C_2 = h \cdot (n1 \cdot D1 + n2 \cdot D2 + \frac{sep3}{l} \cdot D3)$$

This formula does not have any direct physical meaning but weighs the criteria following the intended parameters. Larger values for the parameters reduce the constructability of the element. Each rebar is weighed by its diameter, as thicker rebars are harder to be placed, in the same way, the height increases the constructability as it lowers showing the negative effect of it. It is also low in computational cost and considers the most influential parameters.

-Working time invested

As previously discussed, one of the most accurate values for the constructability is the time spent by the working crew to build the element. This criterion quantifies the number of hours needed to accomplish it and takes into account the different considered factors and interactions between the defined parameters. The standard amount of time for each of the considered operations differs from country to country, but there are databases where an accurate estimation can be obtained. This criterion is split into different sections.

$$C_{3a} = [(h \cdot w + cov)] \cdot t_{3a}$$

The first section takes into account the time spent in shaping the element or how its external shape and contour factors affects the time spent. The parameter t_{3a} measures the time spent to position the element in the building measures in m^2/h.

$$C_{3b} = [\sigma_{hom} \cdot \left(n1 \cdot D1 + n2 \cdot D2 + \frac{sep3}{l} \cdot D3\right) \cdot (con.)] \cdot t_{3b}$$

$$Homogeneity\ (\sigma_{hom}) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(D_i - \overline{D})^2} \qquad \begin{array}{c} Values\ for\ consistency\ (con): \\ (based\ on\ the\ slump\ test\ results) \end{array} \begin{array}{c} (0-2)cm. \rightarrow 1.1 \\ (3-5)cm. \rightarrow 1.05 \\ (6-9)cm. \rightarrow 1.00 \\ (10-15)cm. \rightarrow 0.95 \\ (16-20)cm. \rightarrow 0.90 \end{array}$$

The second section quantifies the amount of time spent to put the rebars into the right place and distribute them consistently. It takes into account the loss of time due to using different rebar sizes and its difficulty in a placement through the homogeneity of them and also the amount of time spent when dumping the concrete in the cast and its interaction with the rebars. The parameter t_{3b} considers the time spent to develop all these tasks.

$$\begin{array}{lll} if\ h = slab\ height & \rightarrow & C_{3c} = (l \cdot w) \cdot t_{3c} \\ if\ h > slab\ height & \rightarrow & C_{3c} = [(l \cdot w) + 2 \cdot (l \cdot (h - slab\ height))] \cdot t_{3c} \end{array}$$

The third and last section takes into account the time spent in the construction of the formwork and it varies depending on if the element has a higher height than the one in the slab that it is in. The parameter t_{3c} measures the hours spent to build the formwork expressed in m^2/h.

With these three sections we can define the constructability criterion like the following:

$$C_3 = C_{3a} + C_{3b} + C_{3c}$$

-Working time simplified

A simplified version to quantify the working crew time can be done assuming a relationship between the steel weight in the section of the element. The parameter t_4 measures the mean value to build a certain section based on this assumption and is obtained through databases and increased gradually as the amount of steel increases. With this simplification, we can quantify the constructability with the following formula.

$$C_4 = \left[(\left(\sum_{i=1}^{n} n_n \cdot [\left(\frac{D_n}{2}\right)^2 \cdot \pi] \right) \cdot \gamma_{steel})/(h \cdot w) \right] \cdot t_4$$

CONCLUSIONS

The AEC Industry has a tendency to automation and improving the procedures by using digital tools such as BIM environments and Digital Twins. For this several BPS Tools are in development to analyze the building requirements and improve, and optimization algorithms are being used in connection with them to help the professionals to achieve better designs.

In this paper, we have explored the parameters necessary to define a new criterion, the constructability for a specific structural problem, a concrete beam. By using a survey a hierarchy among the different parameters has been created and discovered two sets of parameters This methodology can be used to define the same criterion for a different structural element.

Using this previous survey, four distinct ways to measure the constructability have been defined and their strong and weak points explored to adjust the accuracy of the criterion to the optimization purpose where it is going to be used.

Future Research

The model presented in this paper is not a fully developed model, as we have assumed some simplifications. The different mathematical models for the constructability that have been proposed can be refined taking into account more parameters and will achieve a more accurate result, probably at the cost of more computation time. Further research is required to create a mathematical model able to handle a discrete approach for the rebar disposition, including the analysis of each diameter and position individually.

A comparison among the results obtained with the four definitions for constructability in this paper can be done and tested with real results to properly adjust the mathematical models. This comparison of results will show the ideal cases of optimization for each of the four models.

Also, the movement of the crew along the whole building site and the position of the element itself can be taken into account, to assist the constructability for the complete structure and not to each of the elements or the reduction of trims in the rebars to optimize not only the working time but also to reduce the waste.

Further study is required to be able to mix both types of construction, usually, precast elements tend to have better constructability because the process has a higher level of automation, but this is not always true for simpler elements and the different interaction between the parameters has to be taken into account.

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