Advancing structural design through parametric modelling

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Summary

Parametric models can translate diverse types of phenomena. This study analyses the potentialities and the challenges of implementing it at structural design phase. A bibliometric analysis is conducted to evaluate the dimension and the areas of study in which the technology is implemented in the Brazilian scientific field. The results demonstrate usage potential at structural engineering and a national increasing interest on parametric modelling, despite the current unexpressive contribution.

1 INTRODUCTION

Parametric modelling is based on the use of parametric models, computational representations based on the use of entities that have attributes that can be fixed or variable. In a parametric model, when changing an attribute, the model will adapt, reconfiguring itself and changing its related attributes to obey the new defined value, without the need to delete or remodel the geometry [1]. In possession of the model, the user will be able to make consecutive changes in the values of the variable parameters and being able to analyse multiple scenarios. In a traditional model, all changes must be made manually and the user must change not only the values of the directly modified attributes but also those that are related to them. Around 2003 a novel generation of parametric and associative design systems was born with GenerativeComponents, Grasshopper (Rhinocero's native plugin) and Dynamo, by order of appearance. All the systems link closely to BIM systems, and in other cases can live within then, like Dynamo in Revit, besides the possible integrations with finite element softwares [2].

The traditional structural design process, relies mostly on the engineer's experience and knowledge to obtain the structural solution. Therefore, the question arises: how do we know that the adopted solution is in fact the best solution? For small or commonly shapes buildings, the architectural concept is easy to achieve by having experienced structural engineers, but becomes harder for large and complex ones. Additionally, it becomes more and more important to develop an environmental awareness during the engineer's decision-making process, incorporating parameters that analyse the impact of the structure solution. Therefore, to facilitate the design process, the designers can use parametric models to investigate the location of structural elements, besides their dimensions and material, and asses different structural systems and their several arrangements, to make an informed decision on which solution to choose. It is also possible use the parametric variables as input of optimization algorithms, minimizing parameters such as displacements, material consumption, carbone emissions and footprint, among others.

The need to make constant changes to the design process is the major advantage of using parametric modelling when compared to common CAD modelling methods. In addition, changing any parameter entails necessary changes in all attributes related to it, and it is possible to obtain several combinations of variable parameters, allowing the evaluation of complex models. Finally, the use of parametric models facilitates optimization studies, making it possible to obtain the building's optimal parameters, such as cross-section, dimensions, type of material, type of elements, among others [3]. The present article aims to analyse the potential usages for parametric model during design phase and conduct a bibliometric analysis of the technology in the brazilian scientific field.

2 PRATICAL EXAMPLES

There is an extensive literature of studies in structural optimization using parametric models. This coupling has great potential of usage, and several authors present their views about possible methodologies and approaches to the use during conceptual phases. A two-stage approach for automatic structural design of steel frames using parametric modelling is presented in [4]. The authors develop an algorithm to translate the architectural drawing into structural parametric models of the steel frame, by using the layer properties of the 2D CAD drawings to define the structural elements, like walls, windows, stairs, among others. The entire translation process lasts about 8s, which is much faster than the hours a engineers would have spent. Using the parametric model, the dimensions of the structural elements are optimized, to obtain the ideal solution to the building.

A novel method for structural design of high-speed continuous beam bridges was proposed by [5] in which parametric families of the structural components, composed by the families of box girder segments, the substructure – piers, abutments and pile foundations – and prestressed steel strands are evaluated. By arranging these families, the bridge components are defined. By gathering these components, the structural model is assembled. The author analyses different aspects of the use of a parametric model in the design phase of the bridge's structure, and concludes that it has great potential to be used as a design method, as it gives practical solutions that enhance the efficiency and safety of the users, besides being able to be applied to several similar constructions.

As a way to reduce the economic and environmental costs of construction, [6] searches for the material efficiency of structural elements, to reduce the consumption of concrete and steel while resisting the required loads, for the material constraints of India. Among the investigated strategies, the authors mention the use of waste products such as empty plastic water bottles to create lost formwork in beams. The parametric model using Grasshopper, aims to find the optimal arrangement of the bottles through the beam, with variable parameters of type of bottle, location and rotation around its centroid, as shown in Fig. 1. There was a reduction of 16% in the concrete volume, and the cavity beam resistance was similar to the solid one. The environmental gain through this approach is conquered by reducing the concrete but also by incorporating waste products to the structure.

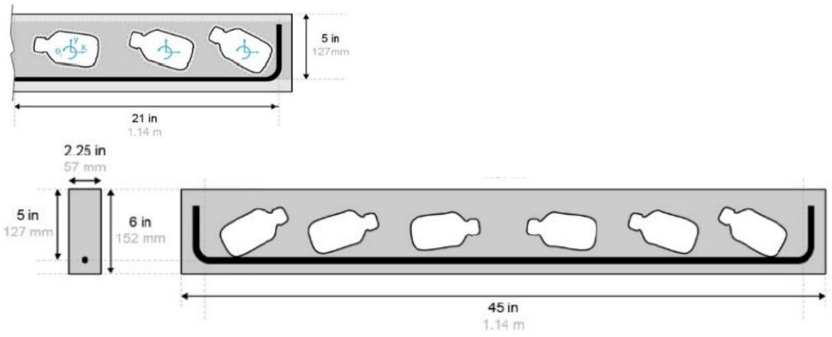

Fig. 1 Top: Wate product's parametric model; Bottom: Resulting arrangement of the bottles through the beam [6].

Despite not having a widespread use, there are practical examples of parametric models use during conceptual phase. The Aviva's Stadium roof, from Dublin, shown in Fig. 2, was entirely designed using parametric model in GenerativeComponents software. The architects and structural engineers shared a single parametric model, and all the changes made by the teams were stored in spreadsheets, so they could revisit a version if necessary. As the sizes of individual members were parametric variables, it was possible to optimize the structure and the engineers were able to analise it's behaviour. The constant flow of information among the two disciplines was important to the final solution, and was only possible due to the parametric model from the very beginning [7].

Arup, a architects and engineer's collective, has used parametric modelling in Grasshopper and GenerativeComponents as a way to improve the behaviour of the designed buildings, through optimization and design variations, such as the structural design process of a curved highway bridge in the United Kingdom. From a parametric model of the proposed bridge, in which variable parameters such as cable arrangements and the pylon and abutment locations were defined, as shown in Fig. 3, the architects and engineers could perform changes and visualize the resulting arrangements in real-time. Using the technology, the team was able to obtain the bridge's general arrangements in a single workshop, rather than prolonged discussions. Additionally, they didn't have to develop all the sketches and go through the entire review phase to add comments and align the project's main requirements, being a time-saving process in comparison with the standard approach. Finally, because of its parametric nature, the model is re-usable in similar future projects [8].

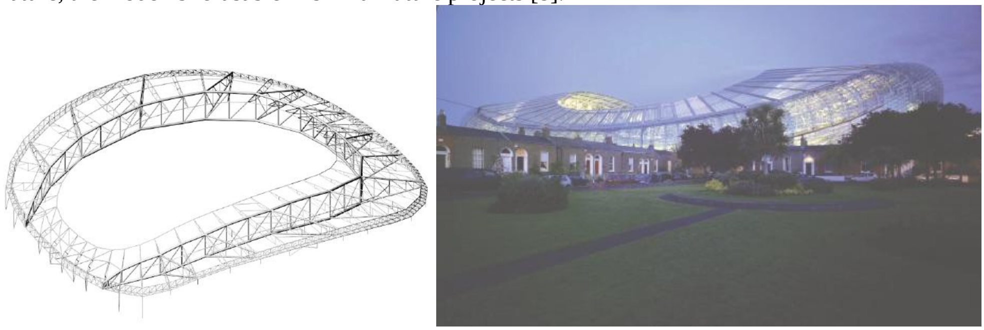

Fig. 2 Left: Resulted structural members from parametric model; Right: Photo of Aviva Stadium (at final stages of construction)[9].

Fig. 3 Left: Parametric model of the bridge; Right: Real image of the bridge [8].

Another success case, was the competition to development of the structure de Austrian Pavilion for the EXPO2010 in Shanghai, China. The architect's design was a geometrically complex surface, as shown in Fig. 4, so the Arup's engineers used a parametric model to demonstrate to the jury that was possible to build the structure within the limited timeframe and a tight budget. Further, the parametric approach allowed the engineers to quickly assess the structural alternatives in face of the architectural changes, besides enabling the development of a building sequence proposal. The collective's engineers also used the forementioned approach to obtain the structural solutions of other buildings with complex geometries, such as the scheme design for Costal Canipies, the NSP Arnhem transfer hall, a large freeform concrete shell, and the Kurilpa tensegrity bridge in Brisbane, Australia [8].

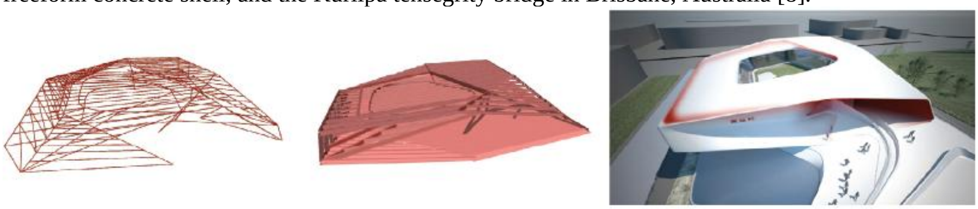

Fig. 4 Left: Parametric model of the structural elements; Middle: Rendered structural model; Right: Architectural image render of competition entry [8].

The technologies employed by engineers for the structural design of atypical skyscrapers, in United Arab Emirates, is examined in [10]. Among the different approaches, the authors mention the case of the engineer's collective SOM, responsible for the structural designs of Burj Khalifa and Cayan Tower, in Dubai, shown in Fig. 5. They developed and applied a computer design plus optimization system when designing the Burj Khalifa. The system integrates several technologies as Algorithmic Design, 3D Parametric & Associative Geometric, Performance based Design, Integrated Design Tools, and Design Automation. By using this system, that allowed exchange of data between different computational tools, such as Rhinoceros, was possible to optimize the structural alternatives.

Fig. 5 Left: Burj Khalifa, Dubai; Right: Cayan Tower, Dubai [10].

3 BIBLIOMETRIC ANALYSIS

In order to understand the state of the art of parametric modelling in Brazil, a bibliometric analysis was carried out in the scientific databases Web of Science, Engineering Village, Scopus and Scielo. It is expected to obtain data on the areas of application of the technology, based on the hypothesis that the publications on the subject reflect the technology's scenario. To obtain indicators closer to reality, the research will be structured to exclude publications that address non-parametric models, since the individual analysis of the entire set of publications on the subject is an exhaustive task. Table 1 displays the set of keywords and rules used in each database search.

The research obtained a total of 733,229 results that encompass publications that mention parametric and semi-parametric modelling in their titles, abstracts or keywords, distributed among the databases as shown in Table 1. The study on the subject begins with an analysis of the progression of publications over the years, as shown in the graph of Fig. 6, in which the markers present the maximum number of publications and the first one for each database. The first publication on the subject dates back to 1952, and for the next 37 years this number did not increase significantly. The maintenance of low numbers is probably caused by the lack of algorithms or computers capable of using the type of modelling. From around 1989, however, there was a change in this trend of stagnation and the number of publications began to grow. From this point on, the scientific community began to research and apply parametric modelling, and consider its use in their respective fields of research.

From this breakdown of the number of publications, USA, China and United Kingdom have a clear predominance, occupying the top 3 worldwide positions, as presented in Table 2. It is also observed that the Brazilian contribution is still small, as the country occupies the 16^{th}, 17^{th} and 18^{th} position in Web of Science, Engineering Village and Scopus, respectively. This data demonstrates how the country is still in its initial phase of research and application of parametric modelling, as the country has a contribution of less than 2% in all forementioned platforms. The data of the database Scielo reflects another scenario, because gathers a set of brazilian journals, reflecting on majority of brazilian authors. Further analysing the data, Brazilian contributions on the subject began in 1973, but started a more robust trend around 2005, as show in Fig. 7.

Table 1 Input of keywords in each database and number of publications obtained through bibliometric analysis

Database	Keywords	Publications
Web of Science	"parametric model" OR "parametric modelling" OR "semiparametric model" OR "semiparametric modelling" NOT "non-parametric model" NOT "non-parametric modelling" NOT "non-parametric model" NOT "non-parametric modelling"	161,927
Engineering Village	"parametric model" OR "parametric modelling" OR "semiparametric model" OR "semiparametric modelling" NOT "non parametric model" NOT "non parametric modelling" NOT "non-parametric model" NOT "non-parametric modelling"	146,774
Scopus	("parametric modelling" OR "parametric model" OR "semiparametric modelling" OR "semiparametric model") AND NOT ("non-parametric modelling" OR non parametric modelling" OR "non-parametric model" OR non parametric model")	23,528
Scielo	"parametric model" OR "parametric modelling" OR "semiparametric model" OR "semiparametric modelling" AND NOT "non parametric model" AND NOT "non parametric modelling" AND NOT "non-parametric model" AND NOT "non-parametric modelling"	401
Total		733,229

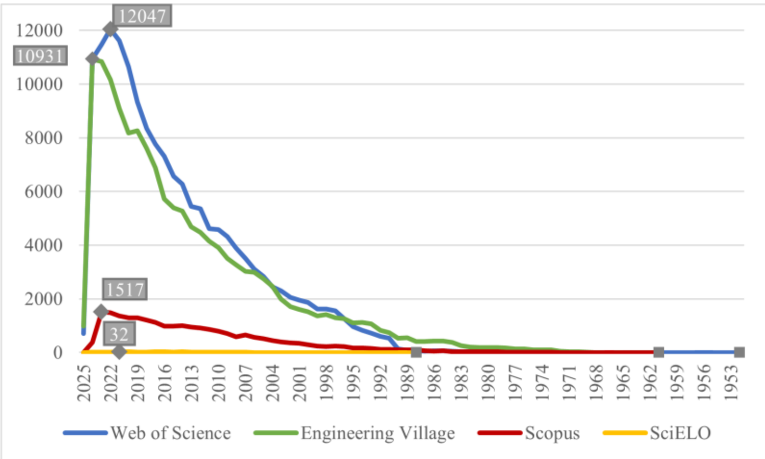

Fig. 6 Publications on parametric (and semi-parametric) modelling through the years according to the databases

Table 2 Countries number of publications on each database

(Country)	Web of Science	Engineering Village	Scopus	Scielo
United States	41925 (25,9%)	33408 (22,8%)	6568 (27,9%)	-
China	32322 (20,0%)	28798 (19,6%)	4454 (18,9%)	-
United Kingdom	11463 (7,1%)	9578 (6,5%)	1721 (7,3%)	-
Brazil	2916 (1,8%)	2313 (1,6%)	342 (1,5%)	188 (46,9%)

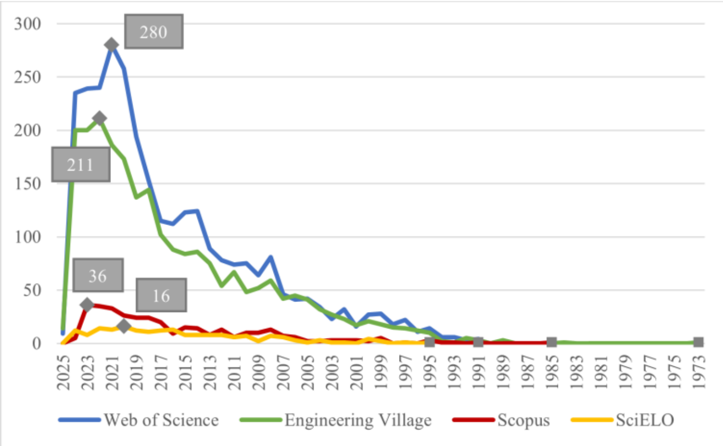

Fig. 7 Brazilian publications on parametric (and semi-parametric) modelling through the years according to the databases

By deepening the analysis of the data referring to the Brazilian scenario, it is possible to discriminate the areas in which the publications on parametric modelling are inserted. The data analysis, show a predominance of the use of modelling in exact sciences, such as engineering, mathematics, computer science, among others, as they are the areas in which implementation is most feasible. The reasoning is simple to understand: parametric modelling can be used to model any phenomenon, however, to obtain a satisfactory analysis, the starting premise is a definition of rules that translate such phenomenon and its possible transformations correctly. As engineering, mathematical or computational problems are more easily translated into rules and functions than social or biological phenomena, that may depend on variables that are difficult to define and quantify, the use of modelling becomes easier for exact sciences.

A more refined analysis was carried to better understand the national applications at structural engineering. After applying the websites' filter tools to the Civil Engineering field and subjects of Structural Engineering and Structure Design, it was possible to obtain exclusively the set of publications of interest. To visualize the most approached topics, the word cloud presented in Fig. 8 was created, with a list of the gathering publications' keywords. In this visual tool, the words with the most repetitions are presented in bigger sizes, so it can be easier to identify terms used more often. Considering that the keywords should reflect the focus of the study, the analysis of a word cloud is expected to be representative.

Fig. 8 Word cloud made from keywords of Structure Design publications

The great appearance of the word Behavior indicates that the parametric models studies have been used predict the structural behaviour of an entire buildings or it's structural components isolated. The set of words Strength, Resistance and Concrete, may indicate that the models have usage in selecting materials and analysing their effectiveness on the structure solution. As for the set of terms Finite-element-analysis (FEA), Optimization and Performance, indicates that the models have been used to enhance buildings' performance through optimization, using the results of FEA. The reoccurrence of this terms among the publications indicates that the structural engineering fields has used parametric models more and more as a way to obtain better results.

Among the several national studies, an automatic verification algorithm for rigid reinforced concrete frame was proposed by [11], considering sensorial acceptability established by brazilian design standard, NBR 6118. The method is a novel way to approach the conceptual phase of structural engineering. The article presents the methodology of development of a parametric model, in which parameters like structural spans and the cross-section sizes are used as input in optimization algorithm to investigate the structural efficiency of the frame. Fig. 9 shows the concrete frame parametric model. Comparison of the results from the proposed method and the ones from commercial software TQS are compared to establish the algorithm efficiency. The author evaluates the algorithm as a tool to assist the engineer's decision process, instead of replacing the currently used ones. In addition, suggests changes and improvements to the algorithm, that can increase its accuracy and potential for disseminating usage.

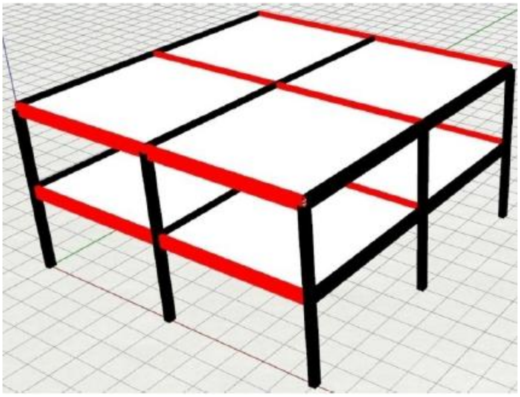

Fig. 9 Concrete frame parametric model, on which the red beams indicate elements with at least one sensorial acceptability problem [11].

4 CONCLUSIONS

Parametric modelling has great potential for use in the structural design phase. By using parametric tools, not only the process of decision making during the conceptual phase can be optimized, but also the buildings that result from it. Through preliminary simplified analyses the engineer can test scenarios and visualizing the structural behaviour, maximum displacement and other structural responses, decide the most efficient arrangements of the structural elements, incorporating environmental parameters, like carbon footprint. Such versions will pass through a more detailed analyses, to confirm if they are in fact appropriate solutions from the structural and environmental perspectives.

The examples of novel parametric modelling methodologies make it clear that it is a technology worth to be known. The new usage possibilities and algorithm that emerge from the forementioned studies can become an important base to consolidate unified approaches for the different types of structure. The article also showed that the use is not only theoretical and there are structural engineers around the world employing the parametric models to facilitate the design phase, especially for architectural complex geometries. Even though this type of modelling can be very useful in challenging designs, in which the engineer may have to analyse several scenarios, it still exists a demand for automation between parametric modelling and the structural dimensioning and detailing softwares. Currently, the modelling process is usually complex, and depends on difficult parameterizations. For such reason, the entire process is longer and don't compensate for the engineer's routine. Further studies on how to enable the technology's use are in need.

Considering its great potential, researchers' interest throughout the world have been growing. Brazil is moving towards an increase in the study of its potential for the various areas of knowledge, despite having inexpressive numbers in the universe of publications on parametric modelling. The technology is being increasingly used, and new forms of use are being proposed, which helps the scientific community to understand more how it works, and to develop more effective forms of approaches and applications. The presented study is a first step to evaluate the challenges and potentialities of the technology, and aims to raise questions about the feasibility of its use in future design processes.

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