Acta Sci. Pol.
Architectura 22 (2023), 138–147
aspa.sggw.edu.pl ISSN 1644-0633 (suspended) eISSN 2544-1760 DOI: 10.22630/ASPA.2023.22.14

ORIGINAL PAPER

Received: 12.09.2023
Accepted: 14.10.2023

GENERATIVE SHAPING IN SEARCH OF MATERIAL AND STRUCTURAL OPTIMISATION OF SMALL STRUCTURAL FORMS

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ABSTRACT

In the 21st century, the most advanced digital methods have allowed structure design, analysis and multi-directional optimisation based on multiple parameters. Mathematical algorithms based on proportionality requirements enable the software to create an individual solution for the specified boundary conditions. This is particularly interesting from the point of view of prefabrication and material engineering, which is now more often characterised by the idea of post-Fordism, where the desire for unification does not exclude the creative search for individual solutions. The research presented in this paper attempts to answer how parametric designing conducted on bar trusses can be implemented into the optimisation of structural elements. The methodology employed in the study involved using of parametric design tools to create a symmetrical truss model, assess its advantages and challenges, and consider load cases. The information provided in the conclusion highlights the evolution of parametric design – which has not only revolutionised architecture and construction by inspiring unconventional forms, but has also facilitated the optimisation of design processes, offered new design possibilities and enabled effective control over various modelling aspects, confirming its invaluable role in both architecture and construction.

Keywords: algorithmic design, digital fabrication, generative design, ICT productivity, interdisciplinary design, parametric design, structural optimisation

INTRODUCTION

Parametric modelling, parametric design and parametric architecture are increasingly used to refer to building design where digital tools have been used in the execution. This proceeding particularly applies to curvilinear, non-orthogonal forms and any structural elements. Parametric design links the operation of the model to the adoption of ‘parameters’. In computer design, the term was applied in the 1970s by Steve Coons, who proposed a description of curves using parametric equations. The next step was the possibility of using parametric features in digital design, first introduced by Mark Gross in his doctoral thesis in which he found that these features were helpful in typical variable forms. Josef Serrano Gómez applied a clear recognition of the parametric technique in architectural solid modelling in 1993 (Alvarado, Lyon & Cendoya, 2015).

This study analyses tools supporting the parametric design of structural elements and parametric architectural design. The literature review helps identify the direction of development of digital design tools and to determine to what extent parametric modelling improves the design process. Based on the literature review and the examples presented, the

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question arises whether parametrisation and the use of digital design tools facilitate the design of structures. In the paper, a model of the truss structure was presented, created using the visual programming software – Dynamo. The calculations for part of the structure were made in Robot Structural Analysis Professional. The research hypothesis of the study is parametric modelling as a tool to support design.

LITERATURE REVIEW

An early example of parametric design is the model of the temple in the Colonia Güell created by Antonio Gaudi. The Catalan architect began work on the project as early as 1890. Despite not having access to digital design tools, Gaudi demonstrated a high skill level in composing shapes (Markert & Alves, 2016). The architect worked on the design of the column for two years (Fig. 1). Through manipulating simple geometries, he achieved an original form like the organic shape of plants (Dixit, Stefańska & Musiuk, 2021). The sketches, models and drawings left by Gaudi provided sufficient data for subsequent successors wishing to complete the work of the deceased.

Fig. 1. Gaudi's model of the Sagrada Familia temple

Source: own work.

Serrano presented work supplementing Gaudi's design of the Sagrada Familia temple with computer models. These models were based on adjustable intersection surfaces. The surfaces were subdivided into helicoids, hyperbolic paraboloids and hyperboloids. The subdivision procedure enabled accuracy, allowing remote fabrication of stone elements without needing to be sent back to the construction site to match the adjacent details (Serrano, Coll, Melero & Burry, 2022).

Algorithmic thinking

Algorithmic design (AD) is a subset of generative design (GD) that specifically employs algorithms to create of design models. In the case of AD, a distinct connection exists between the algorithm and the resulting design, exists between the algorithm and the resulting design. AD offers a higher level of precision and control compared to GD and frequently leads to designs that are predictable and can be replicated (Caetano, Santos & Leitão, 2020).

The parameterisation of the model is applicable when a change in a parameter (i.e. information) affects the geometry of the form and its structure. Parametric design is not based on an intuitive search for a solution but on a step-by-step technique of introducing variables according to specific rules that produce an initial result. Thinking about the process in this way refers to algorithmic thinking. Architects or designers wishing to assist with a parametric model face the challenge of mastering algorithms based on mathematics (Kurcjusz, Stefańska, Dixit & Starzyk, 2022). The essence of design is to understand the process, but practice in using the software is also essential. Algorithmic thinking allows manoeuvring results, controlling, analysing and optimising the design of the solution space (Lehmann, 2023). The assumptions of a design concept created in the imagination can only be verified and optimised once a parametric model has been created. Since 1990, parametric design has influenced the development of digital architectural design, which can be divided into two parts: conceptual parametric architectural design and structural parametric design.

Conceptual parametric architectural design

Conceptual parametric architectural design focuses on the parameterisation of a design model. In this approach, changes in parameters – which represent critical pieces of information – directly influence both the geometry and the form's overall structure. Unlike intuitive searches for solutions, parametric design relies on a systematic technique of introducing variables according to specific rules. This method yields an initial result, making it an excellent example of algorithmic thinking. In conceptual architectural design, the parameters introduced are the most important – not the shape. Thanks to their variability, the form of the building can be easily configured.

Structural parametric design

In structural parametric design, the data refers to the 3D embedded object (Aranburu, Camba, Justel & Contero, 2023). Parametricity in structural design is used most effectively when designing large structures, airports, halls and tall buildings. This is due to the complexity of the structure, as well as the number of elements required. A small change in the geometry of the form makes it necessary to generate a new analytical model. The frequency of changes and the duration of the design process using traditional methods have sparked the desire to integrate digital architectural and structural models (Bialozor & Olszowski, 2017).

An interesting issue is the parametricity of tall buildings, where the design is created with defined rules in its early stages. Therefore, it is difficult to incorporate changes resulting from analyses or client requests. Unfortunately, using AutoCAD software does not make it easy to modify a whole project consisting of many elements (Khoshamadi et al., 2023). Parametricity in a structural model is a complex process. However, according to Suyoto, Indraprastha and Purbo (2015), it senses the architect's mind in structural design and connects the constructors' design with its form's creators. The structural part of a building is developed after the architectural structure is determined. This approach limits the role of the constructor in solving the problems present in the project. It does not lead to a link between the architect's concept and the structural solution. Emerging tools to overcome the previously mentioned limitations provide a cost-effective solution to explore optional design solutions (Khoshamadi et al., 2023).

Structural optimisation

Optimisation algorithms, considering the structure of the building, have found application – especially in structural optimisation. The traditional structural design uses design variables for which arbitrary initial values are given. Structural analysis is carried out to obtain an answer, and the design variables are modified intuitively. In the final stage, the design process ends when good values of the imposed requirements are obtained, often without considering alternatives or not enough of them. Structural optimisation in structural design offers some advantages, including the automatic finding of design solutions that consider the imposed conditions. In addition, optimisation tools can support a designer's decision-making. If the design solution is unsatisfactory, the designer can change the design parameters, material properties or component geometry. It is also possible to impose additional constraints on the optimisation assignment. When considering complex structures, structural optimisation helps to find a feasible solution and, in situations where the designer does not use the key, provides better insight into the behaviour of the structure. A final aspect that is a definite advantage of optimisation is the trade-off between the structural layout and the associated costs (Hu, Song, Song & Li, 2023).

Defined and quantifiable financial benefits are advantageous when convincing an investor to invest. An example is steel weight reduction, a necessary element during building construction. The algorithm makes it possible to optimise material distribution by adjusting the span of the structural beams more favourably due to choosing a lower story height or changing the steel grade and cross-section of the elements. The optimisation algorithm can also be used to carry out static calculations. The advantage is the non-stereotypical thinking of the program and the ability to carry out hundreds of calculation variants in a short time (Stefańska & Rokicki, 2022).

Topological optimisation

Topological optimisation is a rationalisation method that uses computational schemes to achieve optimised material distribution. However, the user must define a set of loads and constraints in the solution space. Optimisation increases productivity and design efficiency in areas that do not contribute significantly. On the other hand, unnecessary material is removed, reducing the structure's weight and lowering the vibration analysis results (Yildirim, 2022).

Topological optimisation enables the creation of forms using several computational methods. The basis of all techniques is the finite element method (FEM). The use of the method allows for the greatest stiffness of the structural system to be achieved. Evolutionary methods for creating structural forms play a significant role in topological optimisation. In the early 1990s, the evolutionary structural optimisation (ESO) method was developed, which consists of dividing a given volume into sections, enabling a subsequent analysis of the forces acting on the section. The support and attachment points are determined with the forces applied in the next step. Once the analysis has been carried out, the excessive material is removed, leaving only the part necessary to transmit the specified forces. Analysis and removal are repeated until the optimum is reached. This procedure is reminiscent of the adaptation of organisms to live in nature – hence the name 'evolutionary algorithms' (Zwierzycki, 2013). The idea is, therefore, based on evolving the structure toward the optimum by removing the elements with the lowest stresses. Another optimisation method derived from the ESO method is the additive evolutionary structural optimisation (AESO) method. An inverted process logic characterises the AESO method.

The use of the method starts at selected points by adding the necessary material in the places most needed (according to the optimisation criteria). The method has not proved successful in all cases (the solutions are correct, but the material used is too high). These findings resulted in the development of an enhanced bidirectional evolutionary structural optimisation (BESO) procedure. Initially published in 2006 by a team led by Mike Xie, one of the creators of ESO, the BESO method combines the principles of ESO and AESO. It effectively eliminates redundant material while incorporating necessary components in specific areas (Januszkiewicz & Banachowicz, 2017). When comparing the BESO method with ESO, it is evident that the former is considerably more efficient, as it is not limited to the removal of redundant material alone.

MATERIAL AND METHODS

In this paper, a parametric truss model was designed using Autodesk Revit 2023, Autodesk Robot Structural Analysis Professional 2023 and the Dynamo add-on. The script creating the geometric model of the truss was made using in the Dynamo add-in. In contrast, the geometric representation was controlled in the Dynamo view window and Robot Structural Analysis software.

The executed script allows the creation of a symmetrical truss in which it is possible to change the distance between the truss bars, the height of the truss and the number of truss fields. However, it should be noted that the executed script generates correct results when the result $n/2$ is an odd number, where n is the number of truss fields. The model uses three cross sections – TREC 80×80×8, HEB 220, HD 360×196 – and defines support conditions.

Combining the Dynamo add-on with the Robot program generated the quantities necessary for further calculations. To perform the model integrated with the Robot program, the following load cases were assumed (calculations of the values of the forces entered the program through the Dynamo add-on are summarised later in this paper):
- permanent loads,
- uniformly and unevenly distributed snow loads,
- wind loads, four cases,
- service loads.

The tools used to design the model made it possible to determine the benefits parametric design brings and the difficulties encountered.

Design tool

The script creating the truss geometry was created in the Dynamo add-on. To execute the algorithm, selecting the necessary design assumptions was performed. An essential element is the selection of the truss type. It should be noted that the script generates a symmetrical truss model, so it is necessary to specify the

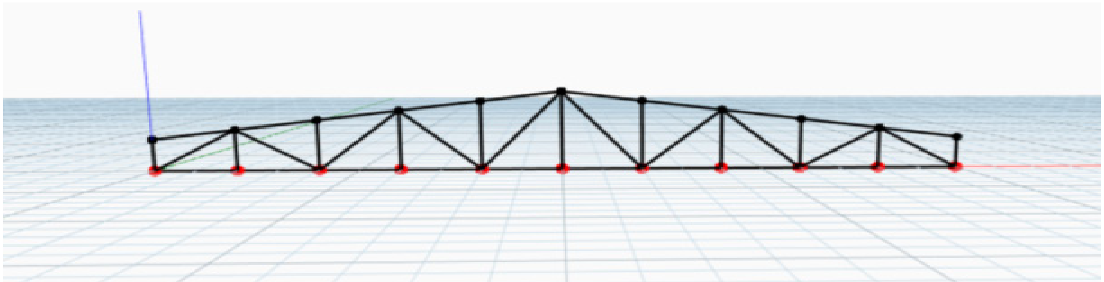

Fig. 2. Truss model made with a script in Dynamo

Source: own work.

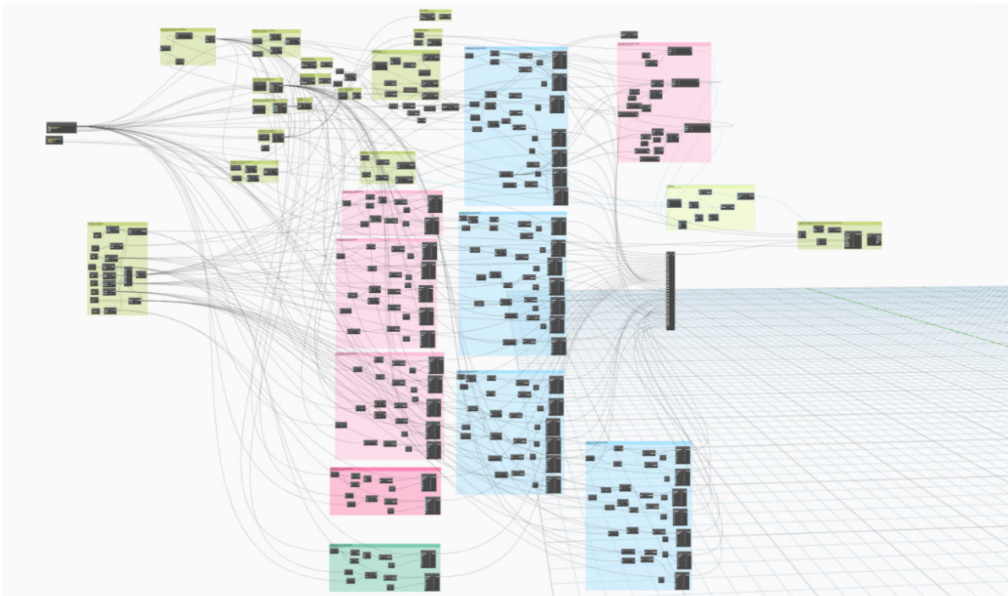

Fig. 3. The overall look of the script in the Dynamo add-on

Source: own work.

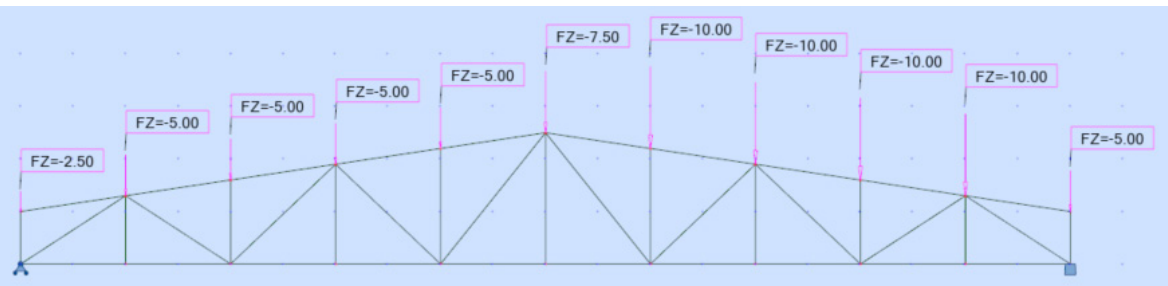

Fig. 4. Final geometry imported to robot structural analysis

Source: own work.

appropriate value of '*n*' in the case of the script executed (Fig. 2). The result *n*/2 is an odd number.

The initial part of the script began by giving parametric values in the code block node (Fig. 3). The following were defined: the number of truss fields, the distance between truss posts and the truss heights. The essence of the created algorithm is the ability to change the geometry of the truss by changing the listed parameters without additional modifications. Figure 4 presents the robot structural analysis visual representation of the generated structure with all loads and loads cases.

Figures 5 and 6 visually illustrate the transformative potential of parametric scripting in architectural design. Parametric scripting empowers designers to create intricate, adaptable geometries responsive to various parameters. This fosters design innovation, streamlines processes and enhances adaptability and sustainability through automated updates and modifications.

RESULTS AND DISCUSSION

The gathered loads from each case were applied to the structure. The calculations were performed using Robot Structural Analysis 2023.

The designed truss geometry modelling script allows changing the shape by changing parametric values. The presented algorithm includes truss heights, truss post spacing and the number of truss fields. In addition, it is possible to select the sections used in Robot Structural Analysis 2023 using the script.

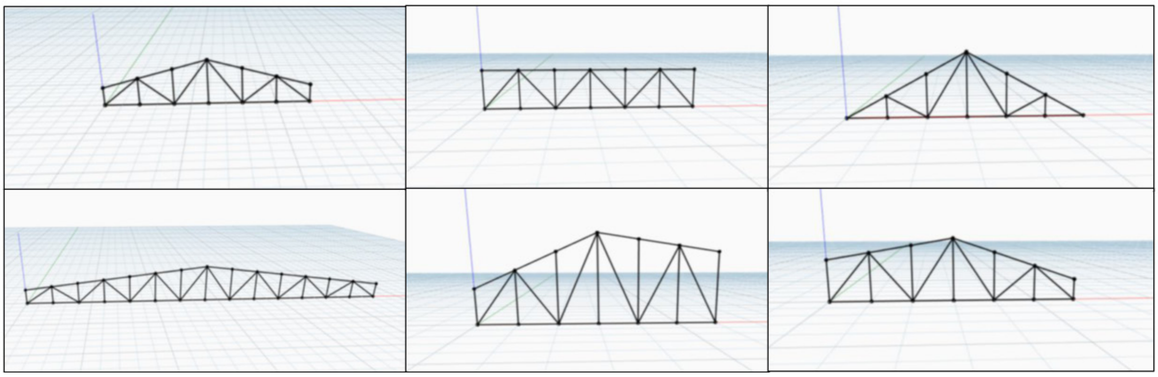

Fig. 5. Different cases created by changing the parameters of the script

Source: own work.

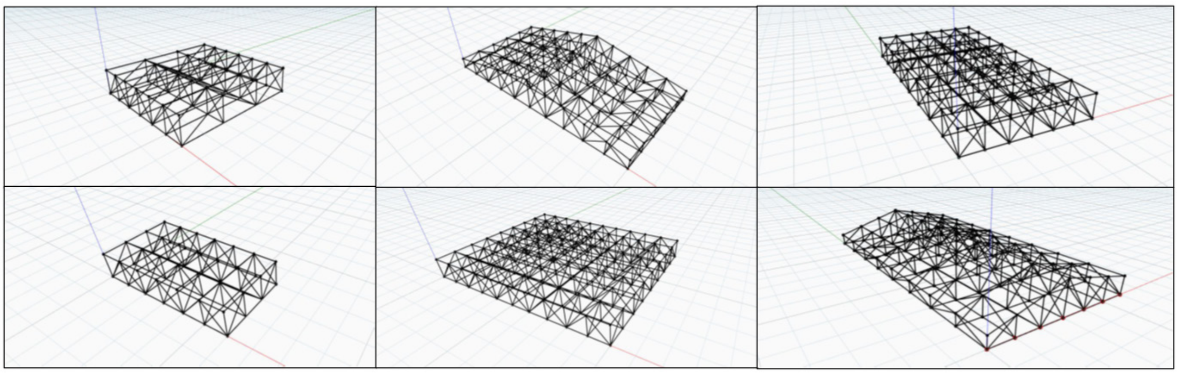

Fig. 6. Different cases created by changing the parameters and extending the script

Source: own work.

The analysed truss structure was created with the following parametric values: $n = 10$, $h_1 = 1$, $h_2 = 1$, $h_3 = 2.5$, $d = 2$.

Using Robot Structural Analysis 2023, static--strength calculations were made and sections were selected for the designed truss. Using the analysis in Robot, 246 combinations in ULS and 83 combinations in SLS were generated. Twenty-four truss elements were considered in the analysis, and sections were selected considering the ultimate limit state. In the case of the first element (bottom chord), case ULS189 was selected as the case of the most stressed element. An HD 360×196 section was selected to meet the given criteria.

For the first and second element, which form the top chord of the truss, the ultimate limit state was maintained for ULS189 and ULS192 using the HEB 220 section.

The posts and cross-braces of the truss were designed from TREC 80×80×8 pipes. All elements were made of S355 steel.

It should be added that in the case of the algorithm, the user is not limited to generating a single result. In the case of the presented script, there are other solutions that, despite the change of the truss geometry, are compatible with Robot Structural Analysis and Revit. The following section of this paper presents examples of truss geometries created by changing parametric variables.

The designed script can generate various types of 2D geometry; however, it is possible to extend the algorithm to create 3D geometry. The modelling of 3D elements from the already created geometry is possible by using, for example, translations by given sizes.

Using several nodes in the Dynamo script, the resulting truss was copied and shifted by a given distance. This step was repeated the desired number of times.

The introduction section of the text sets the stage by introducing the concept of parametric design and its relevance in architecture, especially in the context of digital tools and structural elements. It lays the foundation by explaining the use of parameters in design. The subsequent literature review section delves deeper into the topic, examining historical and contemporary instances of parametric design in architecture. It highlights how architects like Gaudi applied parametric principles to create innovative structures. This section provides theoretical and historical context to the discussion.

Towards the end of the introduction section, the text introduces the truss experiment as part of the broader conversation about tools that support parametric design. The truss experiment serves as a practical example of how parametric modelling tools can be applied to structural design, demonstrating the principles discussed in the previous sections.

The truss model aims to showcase the advantages and challenges of parametric design in structural engineering and architecture. It allows for the parametric manipulation of the truss's geometry by altering parameters such as the number of truss fields, the distance between truss posts and the truss heights. Through this experiment, one can explore how changes in these parameters impact the overall design and structural integrity.

The truss experiment functions as a case study, illustrating how parametric modelling can be used in the design of structural elements. It provides a platform for designers and engineers to iteratively test different configurations, optimising the design to meet specific requirements. Additionally, it underscores the potential benefits of parametric design in terms of efficiency and adaptability.

The designed script can generate various types of 2D geometry (Fig. 4). However, extending the algorithm to create 3D geometry is possible. The modelling of 3D elements from the already created geometry is possible by using, for example, translations by given sizes (Fig. 5).

Using several nodes in the Dynamo script, the resulting truss was copied and shifted by a given distance. This step was repeated the desired number of times.

The presented way made it possible to extend the script uncomplicatedly. The result is the creation of a parametric 3D geometry in which it is possible to change the spacing between the posts, the height of the posts, the number of fields and with further expansion of the script, the length of the grate in the direction of the y axis.

In the following section of the paper, different variants created by changing the parameters of the extended script are presented.

Parametric modelling supports the design process by enabling the creation of designs linked to adjustable parameters. These parameters act as variables governing the geometry and structure of a design. Instead of relying on intuition alone, parametric models offer a systematic and rule-based approach to design. They facilitate design by allowing for the manipulation and optimisation of design solutions according to specific rules and mathematical algorithms. This approach enables designers to explore various design alternatives, maintain consistency in design elements and efficiently respond to design challenges and changing project requirements. In essence, parametric modelling provides a structured framework that enhances creativity and problem-solving in the design process.

The presented parametric design of the truss structure differs significantly from the traditional one created only in Robot Structural Analysis 2023. The created script allows changes by altering a single parameter and their simultaneous implementation into the calculation program. In the presented parametric design, it is possible to change the geometry in terms of the spacing between the truss posts, the number of truss fields and the height of the truss. When using the Dynamo add-on and the algorithm presented here, it takes a negligible amount of time to make the change since it involves changing the value of the code block entry. Another significant advantage is that there is no need to model the structure from scratch in the Robot program. A typed change in the algorithm and running the script will automatically model the truss in the calculation software. Another advantage that encourages the user to use algorithms is that it saves time and promotes more frequent design changes.

Another advantage is the ability to add load cases and individual load values combined with the transparency of the Dynamo add-on. Using groups in the algorithm allows you to control the applied loads without switching case windows (as with Robot) and constantly view the applied values. An undoubted advantage is the ability to change the cross-sections used in individual parts of the structure. The converted algorithm uses three sections: top chord, bottom chord, posts and crossbeams. At any time, the script user can change the cross-section of a given element through the algorithm, which can be a significant time-saver in the case of complex structures. The presented script is extensive, but it is essential to note the versatility of the presented project. The paper includes nine sample geometries for which the script gives correct solutions. The generated trusses were created by making changes to the five parametric variables of the script. After running the script, each geometry was simultaneously generated in Robot with load cases prepared, loads applied supports used and cross-sections specified for each truss element. Thus, there is no need to model the elements from scratch in Robot, and changes are implemented when the script is run.

CONCLUSION

Parametricity is an exciting issue in both architecture and construction. It has inspired and led to unusual forms for many years. Algorithmic thinking is not limited by digital design tools and is considered its basis. An example is the early parametric work of architects such as Gaudi or Serrano. The development of parametricity aroused an increasing desire to optimise work and present new design opportunities. With the passage of time and the emergence of new iconic buildings, there was a desire among their creators to reach higher above traditional building-design thinking. This led to the beginning of the parametric period.

Parametric model control should be mentioned as an essential advantage. This control relates to the model's geometry, the amount of materials used, the layout and, taking into account the structural aspect, the model's strength. The occurring trend of using evolutionary algorithms in design activities is increasing – starting with evolutionary optimisation (EO) and distributed optimisation (PSO), it is common among authors to achieve better and faster performance of individual algorithms. The referenced scientific articles show new developments internationally by budding architects, which are used for optimisation worldwide. It proves that even architects without much design experience can realise more advanced analyses in a much shorter time compared to the previously referenced parameterisation pioneers.

Parametric design is mainly focused on architectural activities, but the subject is increasingly used in the construction industry. The presented parametric design of a truss highlights the advantages of the parametric design of structures, which are significantly superior to a traditional design made without the addition of a Dynamo. The presented solution in the project's initial phase may cause difficulties; however, it should be mentioned that despite the problems, an essential part of parametric design is the constant possibility of expanding and making changes to the design.

Further research in the field of parametric design should explore the practical implementation and integration of parametric modelling tools in architectural and construction projects to assess their real-world impact on design efficiency and creativity. Furthermore, exploring the potential for extending parametric design principles to other domains within construction, beyond truss structures, could provide valuable insights into the broader applicability of parametricity in the industry.

Authors' contributions

Conceptualisation: A.S. and K.L.; methodology: A.S. and K.L.; validation: A.S. and M.K.; formal analysis: A.S. and M.K.; investigation: A.S.; resources: A.S., K.J. and R.R.D.; data curation: M.K. and K.J.; writing – original draft preparation: A.S., M.K. and K.L.; writing – review and editing: A.S., M.K. and R.R.D.; visualisation: K.L.; supervision: A.S.; project administration: A.S.; funding acquisition: A.S.

All authors have read and agreed to the published version of the manuscript.

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WYKORZYSTANIE PROJEKTOWANIA GENERATYWNEGO DO OPTYMALIZACJI WIELKOŚCIOWEJ MAŁYCH FORM KONSTRUKCYJNYCH

STRESZCZENIE

W XXI wieku najbardziej zaawansowane metody cyfrowe umożliwiły projektowanie, analizę i wielokierunkową optymalizację konstrukcji na podstawie wielu parametrów. Algorytmy matematyczne, zdefiniowane według wymogów proporcjonalności, umożliwiają w oprogramowaniu stworzenie indywidualnego rozwiązania dla zadanych warunków brzegowych. Jest to szczególnie interesujące z punktu widzenia prefabrykacji i inżynierii materiałowej, którą obecnie coraz częściej cechuje idea postfordyzmu, czyli dążenia do unifikacji bez wykluczania twórczego poszukiwania indywidualnych rozwiązań. Badania przedstawione w artykule stanowią próbę odpowiedzi na pytanie, w jaki sposób projektowanie parametryczne kratownic prętowych można wdrożyć do optymalizacji elementów konstrukcyjnych. Metodologia polegała na wykorzystaniu narzędzi projektowania parametrycznego w celu stworzenia symetrycznego modelu kratownicy, oceny jej zalet i wad z uwzględnieniem różnych przypadków obciążeń. W podsumowaniu zawarto informacje o ewolucji projektowania parametrycznego, która nie tylko zrewolucjonizowała architekturę i budownictwo oraz zainspirowała powstanie niekonwencjonalnych form, lecz także ułatwiła optymalizację procesów projektowych, dostarczyła nowe możliwości projektowania oraz umożliwiła skuteczne sterowanie różnymi aspektami modelowania, co potwierdza jej nieocenioną rolę zarówno w architekturze, jak i budownictwie.

Słowa kluczowe: projektowanie algorytmiczne, produkcja cyfrowa, projektowanie generatywne, produktywność ICT, projektowanie interdyscyplinarne, projektowanie parametryczne, optymalizacja konstrukcyjna