Application of BIM Tools in Parametric and Generative Design for the Conception of Complex Structures

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Abstract. The present research applies the Parametric Design (PD) and Generative Design (GD) for the generation of complex structures, through the BIM methodology, being implemented in design phase of a new modern proposal for Pavilion J1 of the National University of Engineering from Perú. The research aims to: Study the PD and GD considering the interoperability provided by BIM tools, propose procedures that help solve PD and GD problems, understand the benefits of process automation through generative and parametric algorithms. The conception and design phase of projects are developed in a traditional way using CAD Softwares for drawing plans or BIM Softwares for the design and/or modeling of structures, carrying out manual tasks either for the extraction of measurements, exchange of information or modeling, this implies a lack of efficiency in many processes because despite having modern computational tools, the full potential they offer is not used. This is reflected in the productivity of the construction sector as it is one of the lowest compared to other sectors such as manufacturing, commerce, agriculture. Due to this problem, new technologies were studied, such as evolutionary algorithms supported by parametric design for the conception and design of structures. Subsequently, as a test, this new methodology was applied to various types of structures, testing the parametric behavior and understanding the operation of these new methodologies. As a result of the previous tests, key procedures were defined to cover parametric and generative problems, developing algorithms in textual code (Python), visual algorithms and applying generative algorithms (NSGA-II); capable of creating structures automatically adapting to the designer's criteria. Based on the last stage of the PD and GD procedures, the algorithms for the formulation of the structure were implemented in Block J1, demonstrating the applications and benefits in various tasks such as modeling, loads generation, structural design and software interoperability.

1. Introduction
Parametric design is a theme explored several decades ago applied in different professional fields to create complex patterns, geometries that imitate nature or complex figures, whether in art, music, medicine, robotics, architecture and engineering. While generative design, is a tool has been developing with great force and applies evolutionary approaches imitating natural genetic processes, complements parametric design in the search for optimization of a problem to the point that the design is automated, leaving the creation of solutions to the machines. based on the designer's criteria. Being the field of architecture the
most relevant in these methodologies assisted from the beginning by CAD tools which have evolved over the years nourishing with greater geometric, computational and visual capabilities. By exploiting computing capabilities, attractive, modern and futuristic designs have been achieved.

On the other hand, engineering specifically in structural design has a role not least, but dependent on architecture to be able to design complex structures, so that many structural designers with available traditional tools face difficulties in modeling and designing geometries complex, consequently, normally it is resorted behavior, simplifications of the model, artifacts to model an element, this can include human errors due to fatigue in reaching a complex goal all this triggers a series of inaccuracies and errors to represent structures complex.

Through the application of parametric and generative design, it is not intended to create a leading role in the field of the AEC, but rather to seek interdisciplinary and collaborative work of the sector's specialties, this concept clearly refers to the principles of the BIM methodology which through the advances in its tools are encompassing the PD and GD, providing the designer with many more facilities to interact with other professionals, that is, by applying algorithms of the PD and GD it is possible to simultaneously carry out the architectural and structural design, meaning a reduction in time and effort in the design process. Therefore, the capacities of these new methodologies in the conception of a new structure in Block J1 of the National University of Engineering were investigated.

2. Parametric Design

The term is broken down into its base words to understand the topic "parametric" which derives from the word parameter, is related to mathematics and can be defined as a constant or variable quantity that establishes a system [1]. While “design” is the creation of a plan which describes the operation of a structure or some product [2], then on parametric design for the authors Wallin and Wasberg, it is a combination of mathematical concepts with digital tools which they allow design processes to be carried out in a fairly efficient way, the design process relies on parametric digital models, as we know a digital model is made up of components or geometric figures, etc. these elements in turn have the property of being made up of variables or are also considered as parameters that can be fixed or modified, with all possible changes resulting in a wide range of solutions to a certain problem, then the parametric design gives freedom designers to obtain new results without carrying out the process of modeling, modifications, editions, deletions repeatedly for different cases; Through the processes of parametric design it is possible to create very complex structures that were not possible before or required a great effort to conceive and analyze [3].

It is necessary to differentiate the fields types within parametric modeling and design through their applications and benefits to avoid conceptual confusion, as can be seen in Table 1.

| Table 1. Differences between BIM modeling, parametric modeling and parametric design. |
|------------------------------------------------------|
| **BIM modeling** | **Parametric Modeling** | **Parametric Design** |
| Geometry design and modeling tool | Apply parametric design techniques | Using programming codes |
| Allow to manage a construction project | Compatible with BIM modeling and parametric design | Algorithms that interact with the digital model |
| **Product:** Static Model | **Product:** Flexible Model | **Product:** Flexible Model |
For the structural engineer, modern architectural designs represent a challenge to be able to represent them in an analysis program, since it is necessary to be as faithful as possible to the model in order to predict the behavior of the structure. While it is true that modern software has great processing and calculation capacity, but they do not have the appropriate tools to generate complex geometries or facilitate modeling, parametric design is presented as a solution to this type of limitations, the following advantages can be highlighted:

- Parametric design allows us to explore various design options and solutions to problems, thanks to the fact that it gives us freedom beyond what the software establishes.
- The parametric design allows easy changes to both the digital model and its component elements without the need for redrawing or remodeling. Programming a parametric model takes extra effort, but the benefits of being able to modify an entire model instantly allow for faster and broader exploration during design, as well as providing flexibility in the event of a change.
- The architect and the engineer work collaboratively at the same time, that is, both professionals design on the same parametric software, which improves the conception and approach of the project to be carried out. That is, the result of the algorithm programming by the architects can be used by the engineers for the subsequent structural analysis and vice versa to adjust the structure to the results obtained [3].
- The advantage extends to later phases of the design, applying the automation of processes that is achieved through parameterization, it is possible to automate the documentation such as generation of plans, construction details that are extracted from the model, which drastically reduces the hours necessary for these jobs.

3. Generative design

Generative design are innovative techniques and processes applied to interdisciplinary fields, but in general terms it is based on imitating the natural processes of genetic development, natural selection and optimization through the programming of algorithms or as they are known evolutionary algorithms, the main objectives the generative approach is progression and multiplicity, in turn the genetic has its focus on optimization towards perfection [4].

Entering the field of architecture, engineering and construction (AEC), the concept of generative design is clearer compared to parametric design, which has different approaches and concepts. The generative design process aims to create new processes by exploiting computer capabilities for the creation of newfangled solutions [5], there are various methods to perform the optimization of solutions through generative systems in the world of the AEC, such as:

- Automated cell.
- Lindenmayer system.
- Voronoi diagrams.
- Grammars of form.
- Fractals.
- Genetic algorithms.

To optimize a design, it is necessary to consider a multitude of criteria that must be satisfied, which naturally contradict each other and there is no single solution that satisfies all these criteria or objectives, then find the optimal choice taking into account all these objectives It is called Multi-Objective Optimization (MOO), it can be represented mathematically as shown in Equation (1).

$$\text{min} F(x) = (f_1(x), f_2(x), \ldots, f_n(x))$$ (1)
s. a. \( x \in X \)

Where:

\( n \geq 2 ; \) number of objective functions

\( x = (x_1, x_2, \ldots, x_r) ; \) decision variables vector

\( X ; \) restrictions \( \{x|g_j \leq 0, j = 1, 2, \ldots, m \text{ and } h_i(x) = 0, i = 1, 2, \ldots, e\} \)

\( F(x); \) target vector

\( y = (y_1, y_2, \ldots, y_n), y_i = f_i(x); \) is a feasible solution

An existing method of solving MOO problems is Pareto Optimization (Figure 1). Without any type of preferences about the designer's decisions, a set of several valid solutions is produced, these are called dominated solutions, but when optimizing the objective functions, results are found that optimize the variables, these results are called non-dominated and are part of the Pareto frontier, which have the property of complying with the Optimization of the Pareto principle (1906) Expressing mathematically as follows in Equation (2).

\[
A \text{ point } x^* \in X \text{ is Pareto optimal if } \forall x \in X | F(x) \leq F(x^*), y f_i(x) < f_i(x^*) \quad (2)
\]

Figure 1. Representation of the optimal point and Pareto Border

In the research, the generative processes were carried out by applying the genetic algorithms specifically the NSGA II codes, of elitist characteristic that is to say of the combination and descent of solutions, it is chosen to compare the most optimal of both the predecessors and current results in this way more optimal responses are expected in a next generation, another condition they have in common is the search for non-dominated results to form the Pareto frontier [6]. Among the advantages that could be obtained for the development of structures are:

- The generative design allows us to carry out innumerable designs obtaining results and possible solutions in a short time, thanks to the flexibility that parametric design gives us to change variables to modify the model, it is perfectly integrated into the generative design which is in charge of iterating all the possible
combinations, in order to arrive at the optimal design based on the required objectives such as suitable material, building weight, sustainability, comfort, complexity, cost, location, etc.

- Generative design allows us to create structures that are adaptable to the environment by entering the initial conditions and the objectives to be achieved. Generative algorithms are capable of developing and finding the most suitable path for the design.
- The generative design has compatibility with parametric software even with BIM tools, which allows a faster analysis and design of the result, be it structural design, energy analysis, solar, environmental, etc.

4. Procedures in parametric and generative design
The research focuses on the application of PD and GD in the conceptual development and design phase of a structural project. Because PD and GD are processes based on the application of techniques, the flows developed are fundamentally based on the practice of trial and error until the most optimal flow is achieved. Based on experience developing parametric structures, the following procedures are proposed in Table 2

Table 2. Procedures for parametric and generative design.

| PROCEDURES FOR PARAMETRIC DESIGN | PROCEDURES FOR GENERATIVE DESIGN |
|----------------------------------|---------------------------------|
| **BACKGROUND**                  |                                  |
| Initial conditions and restrictions | Design parameters                |
| Set conceptual Goals            | Objective functions              |
| Identify design problems        | Initial Population               |
|                                  | **PARAMETRIC DESIGN**            |
| Application of parametric tasks | Undominated Classification       |
| Parametric algorithm execution  | Selection                        |
| Parametric frame structure      | Genetic Operations: Selection, Crossing and Mutation Tournament |
|                                  | **ANALYSIS**                     |
| Variation of parameters in the Algorithms to generate Results | New generation |
| General Instance Exploration    |                                  |
| Selection of the most suitable solution |                      |
|                                  | **IMPLEMENTATION**               |
| Geometry generation through frames | Selection of optimal design according to preferences |
| Modification and adaptation for the final design | Adapt results to Parametric Implementation |


5. Implementation of the parametric and generative design for block J1

The implementation of these methodologies was carried out through four phases, the first one used parametric procedures to generate a metallic covering of complex geometry that supports triangular panels, while in the second phase the parametric and generative design was combined to generate a reinforced concrete structure that has better performance according to established criteria (location, area, energy, capacity, volume). Then structurally verify the models to finally carry out a modeling and generation of documentation of the structures.

5.1. Implementation of parametric design

Before proposing the geometry and dimensions of a new structure for block J1, various types of structures and shapes were explored and tested, made of reinforced concrete and steel, taking advantage of the versatility that these modern methodologies provide us, to finally adopt as a base form the Infinite Möbius band (Figure 2) which is determined by the following parametric Equation (3a), (3b), (3c):

\[
x = \left( a + v \cdot r \cdot \sin \left( \frac{u}{2} \right) \right) \cdot \cos (u)
\]

\[
y = \left( a + v \cdot r \cdot \sin \left( \frac{u}{2} \right) \right) \cdot \sin (u)
\]

\[
z = v \cdot r \cdot \cos \left( \frac{u}{2} \right)
\]

The equation was adapted to the algorithms and through a series of parametric tasks the desired geometry was achieved. The area available in Block J1 of the UNI faculty of civil engineering is 40.0 m x 40.0 m, so the code inputs were modified to be able to adapt the geometry to the limited space. It is necessary to emphasize that the PD allows the exploration of different results just by modifying a variable in the parametric code, which requires iterative processes until the designer considers the solution obtained adequate.

5.2. Implementation of generative design

As this process was previously described, once the necessary algorithms and processes had been carried out, the following objectives were considered for the computer to start the search for the optimal designs found within the cover according to the following criteria:

- Maximize the volume of rooms.
- Maximize the surrounding area of the structure.
- Establish an area in the range of 479.04 to 529.46 m² to comply with what is specified.
- Minimize both the HLFF and SVR factor.
- Establish a range of lights varying between 3 m. at 7 m. of length.
- Minimize the cost of the superstructure and the entire building.

As a result of a generative analysis, a number of 97 approved and unique designs were obtained that meet the desired criteria. The figure 3 presents an extract of the obtained designs, presenting in Inputs the parameters that control the reinforced concrete structure that is inside the roof, the model shows a simplified representation of the Möbius surface and the shape that would adapt the internal structure, finally, in performance, a radar graph is presented in which each objective level is exposed compared to the other designs, which means a support to the designer to make a decision when choosing the most optimal one, for the investigation it was selected design number 79.

| N° D | INPUTS | MODEL | PERFORMANCE |
|------|--------|-------|-------------|
| 51   | ANGLE  | 0.6   |             |
|      | RADIO  | 12    |             |
|      | WIDTH  | 19    |             |
|      | LENGTH | 20    |             |
|      | #WIDTH | 5     |             |
|      | #LENGTH| 6     |             |
|      | #FLOOR | 2     |             |
| 72   | ANGLE  | 0.7   |             |
|      | RADIO  | 12    |             |
|      | WIDTH  | 19    |             |
|      | LENGTH | 18    |             |
|      | #WIDTH | 6     |             |
|      | #LENGTH| 7     |             |
|      | #FLOOR | 2     |             |
| 78   | ANGLE  | 0.72  |             |
|      | RADIO  | 11    |             |
|      | WIDTH  | 20    |             |
|      | LENGTH | 20    |             |
|      | #WIDTH | 7     |             |
|      | #LENGTH| 7     |             |
|      | #FLOOR | 2     |             |
| 79   | ANGLE  | 0.12  |             |
|      | RADIO  | 10    |             |
|      | WIDTH  | 22    |             |
|      | LENGTH | 22    |             |
|      | #WIDTH | 7     |             |
|      | #LENGTH| 5     |             |
|      | #FLOOR | 2     |             |

**Figure 3.** Extract of 97 results generative design solutions. The performance of the radial graph has been based on 7 objectives, these are: 1-Volume of rooms, 2-Surrounding area, 3-Volume of concrete, 4-occupable area, 5-Project cost, 6-HLFF and 7-SVR.
5.3. Structural Design
The interoperability of digital modeling software was studied; Parametric design with the tools for structural design in order to demonstrate the great contributions of the parametric and generative methodology proposed.

Taking advantage of the algorithms created for the generation of the structure, it was possible to use the same codes to generate the model in a structural design program, as well as the parametric design to assign the transferred loads to each node according to the tributary areas that correspond as shown in the Figure 4:

![Algorithmic automated load allocation](image)

**Figure 4.** Algorithmic automated load allocation

In this way the total weight of the structure is calculated $DL = 107,014.91 \text{ kg}; LL = 95,780.71 \text{ kg}; \text{TOTAL} = 202,795.62 \text{ kg}$. As well as seismic, wind and service loads actions were considered for the design of the structure, obtaining the efforts for its subsequent design of structural elements.

Regarding the seismic study, the ASCE standard - Minimum Design Loads for Buildings and Other Structures and the seismic-resistant rule in Peru E 030 were taken into account, obtaining the following seismic factors.

\[
\begin{align*}
Z &= 0.45 \\
S &= 1.00 \\
T(p) &= 0.4 \\
T(L) &= 2.5 \\
U &= 1.5 \\
R &= 1.25 \\
T &= \frac{hn}{Ct} = \frac{10}{45} = 0.22 \\
T < T(p) &\rightarrow C = 2.5 \\
\frac{Z \cdot U \cdot C \cdot S}{R} &= 1.35
\end{align*}
\]
Seismic weights of structures $P = 174,983.195 \text{ kg}$; basal shear of the structure $V = 236,227.3133 \text{ kg}$. The behavior of the structure before the action of the earthquake is presented in the figure 5:

![Figure 5. Behavior of the structure under earthquake actions](image)

According to the wind map of the E020-Peru standard, it provides wind speeds according to the geographical location of the project; For the case study and research approach, the design speed is 65 km/h, which is why it turns out to be lower than that stipulated by the standard, considering the aforementioned, the speed considered for the design is 75 km/h.

It is necessary to mention that due to the complexity of the structure, the method used to calculate the forces caused by the actions of the wind was Wind Tunnel (Figure 6), a procedure by which a real situation can be simulated in the face of aerodynamic forces.

![Figure 6. Structural analysis due to wind loads - Wind tunnel.](image)

Part of the flow of the structural design is to verify the structure by means of the service loads, presenting in the table three representative elements and of greater efforts before these considerations, observing an acceptable state. These representative elements are presented in Table 3.
Table 3. Verification of deflections due to service loads.

| Nº ELM. | DESCRIPTION   | LNG. (m) | DEFLECTION (mm) | L/360 (mm) | VERIFICATION |
|---------|---------------|----------|-----------------|------------|--------------|
| Bar 21  | Max. height   | 10.55    | 0.08            | 29.3       | OK           |
| Bar 521 | Max. length   | 19.45    | 1.22            | 54.02      | OK           |
| Bar 481 | Max. deflection | 19.41   | 1.68            | 53.92      | OK           |

5.4. Parametric modeling

The parametric modeling in the research consisted of applying the PD algorithm to the automated creation of the model, that is, going from a frame model of lines and surfaces to modeling components of a BIM software (Figure 7). Through algorithms and programming, in such a way that it was modeled only using adaptive algorithms and families.

![Figure 7. Transfer of Parametric Design to a BIM Model](image)

6. Results and discussions

Currently many projects are modeled and designed assisted by computational tools, that is to say in a traditional way the modeler or designer creates element by element of the structure if we add complexity to the structures it becomes a tedious or almost impossible task to complete. Therefore, in this research, he showed that the implementation of parametric and generative design in the conception and design phase allows us to save time and effort in each task of these phases. In addition, the BIM methodology turns out to be compatible with PD and GD to such an extent that in this year many programs come in a single package, however, from the point of view of interoperability of structural design and modeling software they are still under development so the transfer of information is still deficient, but thanks to the use of algorithms it is possible to solve these limitations that arise.

On the other hand, it was possible to conceive a modern structure that is to be proposed as a new proposal for its construction in block J1 of the UNI engineering faculty.

7. Conclusions

The proposed strategies about PD and GD were tested and put into practice to conceive various parametric structures, proving to be satisfactory in all cases, since it allows to have a broader panorama of the problem to be addressed, also to apply it correctly and in the appropriate time the tasks or processes to produce geometries, as well as the formal production of parametric structures.
The research demonstrated the power granted by the PD in the search for new forms for structures, not only applied to buildings but also to bridges, roofs, latticework, sheds, towers, etc. adopting geometries of nature and mathematical formulas. On the other hand, the GD allows to search for the most optimal solutions under the conditions that govern the structure, providing an innumerable number of designs for a problem helping in decision-making.

If the PD and GD are implemented in the development of a project, it is necessary to consider a new role for the BIM programmer or parametric designer, since this is responsible for the conceptual creation of the structure and possible structuring, in addition to the algorithms developed reaching the intervening specialties serving as the basis for the development of the project.

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