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Applications of generative design in structural engineering
Aplicaciones del diseño generativo en la ingeniería estructural

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Abstract

The traditional structural design produces elements that can be improved from the point of view of the use of the material. As a way of perfecting these processes, methodologies such as BIM have emerged, which, although they fulfill their mission of creating information models through collaborative work, their form of parameterization is still limited. In this context, the generative design emerges as a way of designing by stipulating the parameters and restrictions to be met so that the code then delivers different alternative solutions. This document aims to synthesize different generative design applications in structural engineering to extend its use in civil engineering. To achieve this, a literature review, and a survey of professionals in the area were used to obtain their opinion. As a result, seven application cases were obtained, where the main use identified for generative design is the optimization of the amount of material for structural elements. Besides, most of the respondents are unaware or have little knowledge of what this process is about, although, after understanding it, they believe it can be used in their professional practice.

Keywords: *Generative design, parametric design; structural engineering, optimization, BIM*

Resumen

El diseño estructural tradicional produce elementos mejorables desde el punto de vista de la utilización del material. Como una forma de perfeccionar estos procesos, han surgido metodologías como BIM, la cual, si bien cumple su misión de crear modelos de información, a través del trabajo colaborativo, su forma de parametrización es aún limitada. En este contexto surge el diseño generativo como una forma de diseñar estipulando los parámetros y restricciones a cumplir, para que luego el código entregue diferentes alternativas de soluciones. Este documento tiene como objetivo sintetizar diferentes aplicaciones del diseño generativo en la ingeniería estructural, como forma de extender su uso en la ingeniería civil. Para lograrlo se usó la revisión de literatura y una encuesta a profesionales del área para obtener su opinión. Se obtuvo como resultado siete casos de aplicación, dónde el principal uso identificado para el diseño generativo es la optimización de la cantidad de material para elementos estructurales. Además, la mayoría de los encuestados desconocen o conocen poco sobre lo que trata este proceso, aunque, luego de comprenderlo, lo creen factible de utilizar en su ejercicio profesional.

Palabras clave: Diseño generativo, diseño paramétrico, ingeniería estructural, optimización, BIM

1. Introduction

Currently, structural design works with conventional processes that, while compatible with traditional construction methods, also restrict design flexibility. This causes some inefficient structural elements since, in certain cases, more material is used than necessary to comply with the requirements. This produces more expensive systems with greater environmental impact. This situation is starting to change since currently there is the necessary technology to build structures with more complex geometries, thanks to the development of tools such as 3D printers (concrete and steel). This allows the consideration of alternative designs to the traditional (Abdallah et al., 2019).

In order to optimize the design and construction processes, in recent years, methodologies and technologies have emerged that are capable of managing enormous amounts of information in order to change the traditional way of working and thus reduce economic losses in production, reduce design time, avoid constructive conflicts, carry out model simulations, among others (Muñoz-La Rivera et al., 2020).

One of these solutions is the implementation of the Building Information Modeling (BIM) methodology (Singh, 2020), which serves to carry out the design, construction, administration of installations, renovation, and even demolition and is based on an integrated information model of the project that codifies, in addition to its geometry, other aspects such as spatial relations, building components, among others. (Jabi, 2013). BIM works during the whole life cycle of projects to make them more efficient, to allow interdisciplinary cooperation, to increase the level of detail of the model, to test different design alternatives, and so on (Muñoz-La Rivera et al., 2019). This methodology can be applied through software, such as Autodesk REVIT and Autodesk ROBOT.

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Models made under programs working in BIM environments can be used to solve constructive conflicts between different disciplines, divide the model into stages, insert a high level of detail, among others. In order to carry out these tasks, the software mentioned above is supported, among other technologies, by parametric modeling tools, with which essential geometric and spatial relationships are defined and controlled, together with information on each element incorporated, for the creation of a parametric three-dimensional model (Cavieres, 2007). Having said that, in practice, we speak of 6D or 7D, where in addition to the graphic information of the model, the time, cost, operation, and sustainable development are included (Andreani et al., 2019).

Parametric design refers to a form of modeling in which relationships between various parameters, such as the shape, dimensions, and positioning of objects, are specified, with the advantage that the designer can quickly adjust some, and the rest of the model will act accordingly. The readjustment generated in the model from the user's changes is carried out by the software itself based on the rules previously established by the designer (Jabi, 2013). These permutations must be subsequently evaluated to verify that they meet their objective. Unfortunately, the software traditionally used in the BIM methodology offers little flexibility in terms of exploring design alternatives at the preliminary project stage, since the parameterization they offer is reduced to changing the dimensions and characteristics of pre-established elements in the program's libraries, such as walls, windows, columns, and stairs. (Cavieres, 2007).

This is how that generative design arises (Lajas Benéitez, 2019), which allows designers and engineers to define parameters such as materials, spatial constraints, manufacturing methods or cost limitations (Autodesk, n.d.), to create rule sets or algorithms (Lajas Benéitez, 2019) and thus automatically explore various permutations of the model, where the software generates the best design alternatives according to the previously proposed objectives (Autodesk, n.d.). Therefore, in parametric design, it is the user who can easily modify the geometry of the model (or the desired variable) in order to evaluate these variations later. In contrast, in generative design, it is the software that takes the inputs, evaluates them, and thus creates alternatives that best meet the requirements proposed by the user (Cavieres, 2007).

One of the disadvantages of developing a generative design code is that it involves investing time and work on the part of the company or the user. Although on the other hand, it should be considered that the more precise and complete this tool becomes, the greater the time savings in future operational processes that can be solved with such a code (Lajas Benéitez, 2019). Generative processes then emerge to accelerate the early stages of design (Johan et al., 2019).

In general, the use of these tools is associated only with geometry, although in engineering, a generative model comprises a set of rules and physical characteristics, given for example, by the materials, which must be characterized by their mechanical properties (Johan et al., 2019). These parameters serve to describe specific ranges, limits, and dispositions. Then, depending on the problem to be solved, one or other parameters (or combinations of them) will be used. This is an interesting tool to combine variables that at first sight are not so clearly related to each other (such as the limits of a building and solar radiation) and thus build a variety of approximate solutions.

Since civil engineering is responsible for feasibility studies, design, management, inspection and construction of works, operation, and maintenance of structures (Deiana et al., 2018); frequently works with many of the parameters mentioned above. These depend on the branch or subdiscipline being studied since, in each one, different characteristics, behaviors, and properties of certain elements are analyzed (Deiana et al., 2018).

In order to bring generative design closer to civil engineering, this study was delimited to structural engineering (where it has had limited use (Abdallah et al., 2019)), as it is more in touch with architecture, an area which, as it has been deepened, has varied experiences with this process. Therefore, the objective of this work is to compile experiences of the application of generative design in structural engineering, together with an analysis of its respective advantages and feasibility of implementation. All this as a basis to make known, to cement, and to expand the uses and benefits of this methodology in this area and, consequently, in the other subdisciplines of civil engineering.

2. Research methodology

Since this study is of an exploratory nature, it was developed mostly through literature review and data collection. Therefore, the research methodology was organized in three stages: (1) identifying applications of generative design (GD) in structural engineering; (2) assessment of the GD by civil engineers; and (3) proposals for GD applications in structural engineering. The tools, activities, and deliverables of each phase are detailed in (Figure 1).

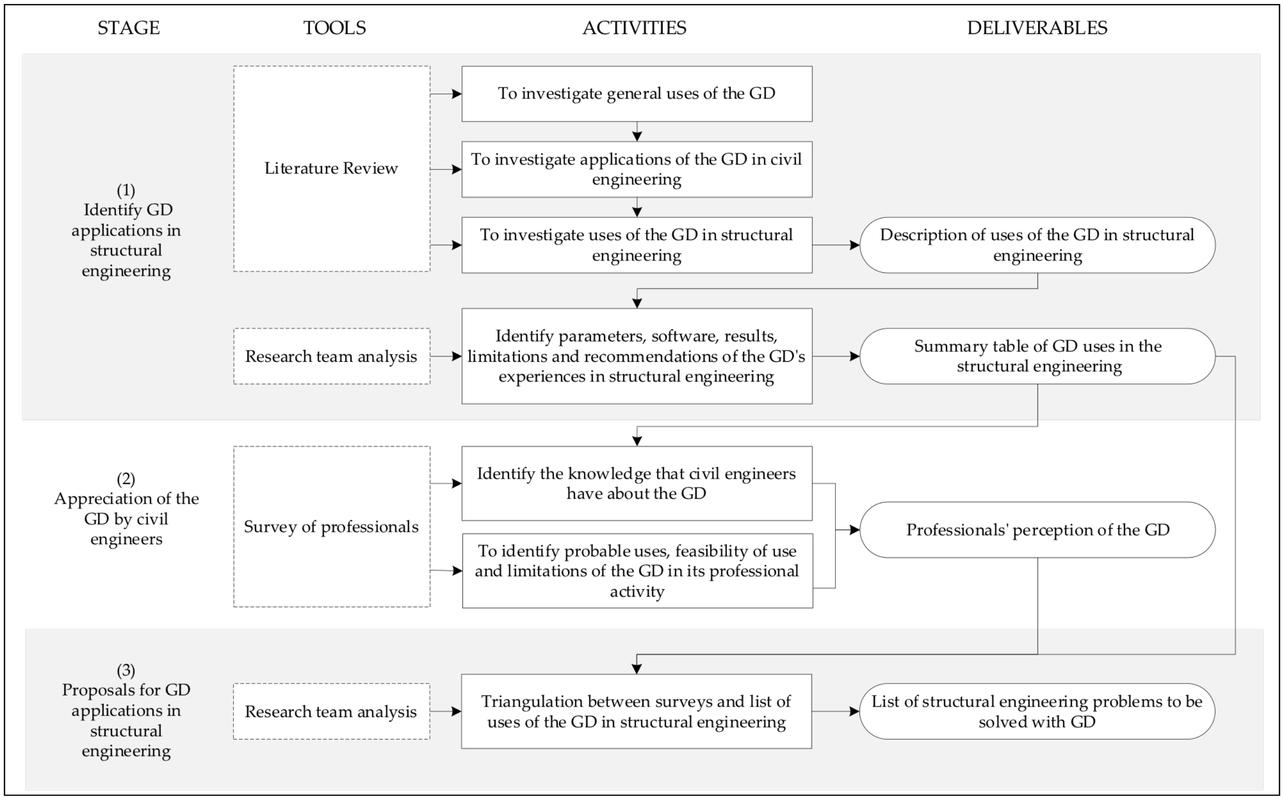


Figure 1. *Research method*

For the literature review in the first stage, databases such as Web of Science, Scopus, Scielo, and Google Scholar were used, using as key concepts "generative design", then adding the word "engineering" and finally "structural" (and their respective English translations) and the Boolean operators "and", "or", and not "not" (Hernández Sampieri et al., 2014). At an early stage, the words "architecture" and "parametric design" were also included, which is where most of the information was discovered, and then excluded (through not), to focus the search on generative design in structural engineering, as can be seen in (Table 1). Finally, 67 documents were read, of which 48 were presented and published between 2005 and 2020.

The results obtained correspond to undergraduate and graduate theses, articles in scientific (and architectural) journals and books, both in Chile and internationally (in Spanish and English), as well as the website of Autodesk and Dynamo (developers of generative design software). The order in which the documents were read was the title, abstract, conclusion, and finally, for the writings relevant to the research, the body. They were compiled using the Mendeley program, and the most recent documents were given priority (the oldest title cited in this writing is from 2007).

Table 1. *Topics covered in each bibliographical reference*

Author/s	Parametric design	Architecture	Generative design	Engineering	Structural Engineering
(Jabi, 2013)	x	x			
(Lyon Gottlieb & García Alvarado, 2011)	x	x			
(Marsault, 2018)	x	x			
(Cavieres, 2007)	x	x			x
(Alfageme García, 2016)	x	x			x
(Gonzales, 2018)	x				x
(Lajas Benéitez, 2019)	x				x
(Muttio, Botello, & Tapia, 2017)	x				x
(Chen, Lu, & Lin, 2005)	x				x
(Martínez-rocamora, García-alvarado, Casanova-medina, González-böhme, & Auat-cheein, 2020)	x	x		x	x
(Jige Quan, 2019)	x	x	x		
(Betancourt, García Alvarado, & Quintero Villarreal, 2012)	x	x	x		
(Salcedo Lagos, 2012)	x	x	x		
(Touloupaki & Theodosiou, 2017)	x	x	x		
(Lyon Gottlieb & García Alvarado, 2011)	x	x	x		
(Dennemark, Aicher, Schneider, & Hailu, 2017)	x		x	x	
(Chang, Saha, Castro-Lacouture, & Pei-Ju Yang, 2018)		x	x		
(Rodrigues et al., 2018)		x	x		
(Zhang, Tong, Huang, & Zhang, 2019)		x	x		
(Velasco, 2015)		x	x		
(Wang, Janssen, Chen, Tong, & Ji, 2019)		x	x		
(Cichocka, 2015)		x	x		
(Singh & Gu, 2012)			x		
(Cocco, 2014)			x		
(Rodrigues, Amaral, Rodrigues, & Gomes, 2015)			x	x	
(Oh, Jung, Kim, Lee, & Kang, 2018)			x	x	
(Marinov et al., 2019)			x	x	
(Jarquín Laguna, 2014)			x	x	
(García Alvarado & Lyon Gottlieb, 2013)	x	x	x		x
(Bertollini, 2019)		x	x	x	x
(Bonelli & Gudiño Gutierrez, 2015)	x		x		x
(Van Telgen, 2020)	x		x	x	x
(Hofmeyer & Davila Delgado, 2015)	x		x		x
(Plocher & Panesar, 2019)	x		x		x
(Johan et al., 2019)			x	x	x
(Turney, 2020)			x	x	x
(Abdallah et al., 2019)			x		x
(Paschke, Neuhäuser, De Rycke, & Gengnagel, 2019)			x		x
(Herr & Fischer, 2013)			x		x
(Reintjes, Hartisch. Michael, & Lorenz, 2018)			x		x
(Daicong, Xia, Guangyo, & Huang, 2017)					x
(Uarac, Cendoya, & Sanhueza, 2015)					x

In the second instance of the research, online surveys (with open and closed questions) were conducted through the SurveyMonkey platform that was answered from 24 August 2020 to 11 September 2020. The instrument was aimed at civil engineers involved in structural design.

In the first section of the survey, the respondents were characterized to be referred to one of the two forms of the second section of the survey (A and B), as indicated in (Table 2); the first one for those engineers who declared to have worked with generative design, while the second one was applied to those professionals who expressed to be unfamiliar with the methodology, or to know it, but not to have worked with it.

Respondents who stated that they had used the methodology were asked about the problems and benefits they obtained from applying it (open question). In contrast, the other respondents were asked about the possible feasibility of implementation (closed question) and ideas about which process could be optimized with generative design (open question).

Table 2. *Survey section description*

<table>
<tr><td>Part 1</td><td colspan="4">Respondent identification: number of years of experience in designing structures, types of projects usually designed, knowledge, and use of the GD.</td></tr>
<tr><td rowspan="3">Part 2</td><td colspan="2">Form A: Professionals with no experience in the GD</td><td colspan="2">Forma B: Professionals with experience in the GD</td></tr>
<tr><td>A.1</td><td>Explanatory video on the GD (obtained from the Autodesk website) and a summary table of uses of the GD in structural engineering</td><td>B.1</td><td>Experiences, benefits, limitations, and feasibility of implementation of the GD</td></tr>
<tr><td>A.2</td><td>Issues and problems for improvement with the GD, the feasibility of using the GD,</td><td>B.2</td><td>Problems in their professional practice that could be solved with the GD.</td></tr>
</table>

3. Results and discussion

(Table 3) shows some of the variables used in parametric and generative designs. It shows the diversity of the types of parameters, which despite being designed for parametric design, were extrapolated to generative design, as both methodologies share the type of variables to be evaluated, which can be of the type: environmental (about the environment where the structure is located), global (about the general volume or the project envelope), local (about particular elements) and execution (about the execution of some elements) (García Alvarado and Lyon Gottlieb, 2013). Subsequently, its use is exemplified through seven cases of specific applications of generative design in structural engineering.

Table 3. *Parameter Taxonomy (García Alvarado and Lyon Gottlieb, 2013)*

Environmental parameters (EP)	Global parameters (GP)	Local parameters (LP)	Performance parameters (PP)
Geographic data: topography, views, soil types, etc.	General dimensions or proportions: minimum and maximum ranges for length, width, depth, curvature, etc.	Dimensions or proportions of components: minimum and maximum ranges for length, width, depth, quantity, etc.	Production dimensions: the size of materials and execution machines
Climatic data: orientation, temperature, humidity, radiation, winds, etc.	Functional requirements: comfort features, ergonomics, accessibility	Interaction with other components: edge conditions and response to adjacent configurations	Material properties: resistance or bending ranges
Contextual situation: normative restrictions of urban situation, materiality, typology (isolated, paired, tower, plate, etc)	Global distribution: relations and internal topology.	Response to analysis values: depth or thickness of the pieces according to sunshine or structural solicitations.	Product characteristics: colour, texture, finish, etc.
Relations of the environment: pedestrian and vehicular flows, presence of singularities, references, etc.	Expressive conditions: facade configuration and materiality.	Final conditions: gradual variation between components.	Application values: project costs.
Site dimensions: Width and depth of the lot, slope, building limits.	Technical constraints: spans and overhangs according to structural system.	Assembly requirements: types of assembly, joints and expansion between components.	Dimensions for transport: magnitudes of vehicles and operation.

3.1 Generative design application cases in structural engineering

Case A: Modification of the structure for deformation control

As a precedent to this case, we have that (Huang and Xie, 2010) proposed to optimize the material in structural elements (in this case beams) through a hybrid scheme of Bi-directional Evolutionary Structural Optimization (BESO), where instead of removing the inefficient elements totally, these were replaced by components of lower density, complying with that certain point of the final structure satisfied a certainly permissible displacement for a fraction of the initial volume. This methodology (executed through a code in MatLab) was *efficient and showed that as the volume decreased, the structure took truss-type configurations, with bar-type elements in traction and compression (Uarac et al., 2015).*

In another context, given the soil condition in the Netherlands (thick layers of clay on top of layers of sand), high-rise office buildings often have a concrete core for lateral stabilization. In this environment, a central core configuration was created for a twenty-story building (with three lift cars, a staircase, and a central corridor) to vary its dimensioning and find a balance between the size of the core and the smaller base, that is, between making the structure more rigid (and avoiding much wind deflection) and the more economical one. The Packhunt.io and Viktor.ai programs were used, as well as one of Arcadis' own "DynamoRFEM" (together with Refinery) (Van Telgen, 2020).

The length of the part of the wall that has the access door varied from 3 [m] to 6 [m] and the number of piles in the X (4 to 8) and Y (4 to 6) directions according to (Figure 2), resulting in 105 design options that were later filtered out to comply with the lateral deformations of the building between 0.6 and 0.7 [cm]. The results show that this is a valuable tool for making design flexible in the early stages and helps the designer to make decisions that would take much longer to calculate in the traditional way. However, structural data has yet to be linked to a cost estimate (Van Telgen, 2020).

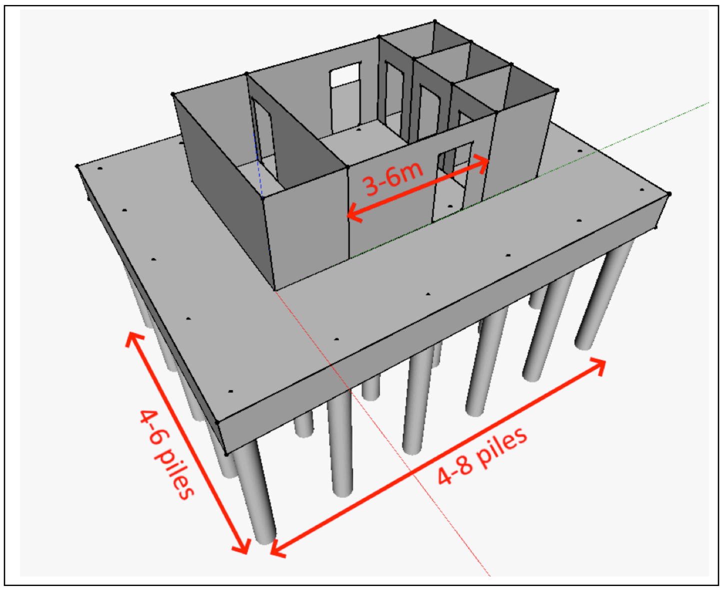


***Figure 2.** Building core to be optimized (Van Telgen, 2020)*

Case B: Cantilever optimization with 3D printing

Today, the 3D printer offers the option of including increasingly sophisticated parameters and criteria in architectural designs, such as analyzing structures with finite elements and thermal behavior. Furthermore, thanks to this greater freedom in design, artificial intelligence, and automatic learning algorithms can be incorporated into the creation process, allowing the designer to automatically evaluate solutions according to some predefined criteria (Martínez-rocamora et al., 2020).

In this work, a design tool was developed for reinforced concrete beams with sufficient structural capacities but using fewer materials and resources. Following the design guidelines of the American Concrete Institute (ACI) code, a cantilever beam was structurally analyzed to relate the geometric parameters to those of structural capacity. The optimization was achieved by minimizing the depth and the steel reinforcement ratio in each segment along its length, starting as (Figure 3 (a)) and ending as (Figure 3 (b)) (Abdallah et al., 2019).

MatLab was used to optimize the beam and calculate the reduction in cost and CO_2 emissions between the conventional structure and the new one. This process resulted in lighter and more economical beams that meet the structural requirements of the ICA. The cost was significantly reduced from 40% to 52% of the initial cost, and the

CO_2 emissions were reduced from 39% to 51%, per beam. Additionally, if this design tool were applied to all similar beams in a building, its impact would be even more significant (Abdallah et al., 2019).

It is important to mention that if the optimized beam (Figure 3 (b)) were built using the conventional construction process, it would be very complicated and slow due to its geometry. Therefore, to comply with the results mentioned above, it was recommended to use 3D printing of concrete and steel to facilitate its execution. Further research suggests following this logic in other structural elements of the building to create fully optimized structures, therefore obtaining greater economic and environmental benefits (Abdallah et al., 2019).

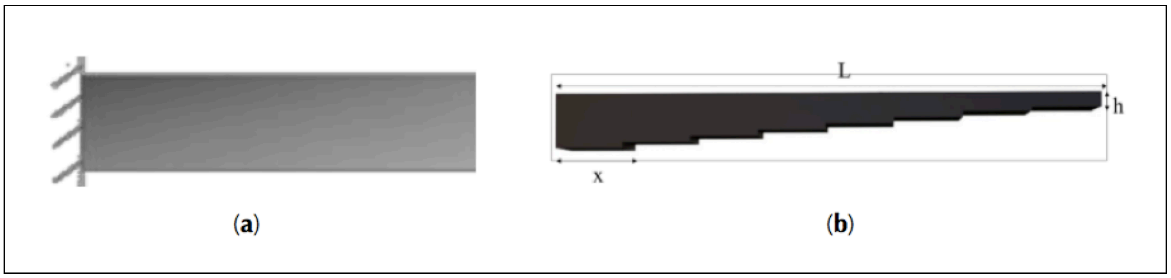


Figure 3. *View of beams on profile (Abdallah et al., 2019) (**a**) Traditional design beam (**b**); Optimized beam*

Case C: Material optimization in slabs

Topological optimization seeks to distribute the material of some structural elements within a certain volume, to maximize its performance while complying with certain restrictions (Uarac et al., 2015). Since slabs are one of the elements that require the greatest amount of material, they are the elements that generate the greatest energy impact in a building because, besides, they are made up of products with high carbon consumption (steel and concrete). For this reason, optimization was carried out with parametric design and genetic code of horizontal square plates with forces outside the plane that could be used as reinforced concrete slabs in a building in a seismic zone (García Alvarado and Lyon Gottlieb, 2013).

The initial analysis was performed in MatLab through finite elements, discretizing the slab two-dimensionally in 60x60 units. The material was reduced by 50% after approximately 30 iterations. Then, moment magnitudes in the different axes and maximum displacements from 3 to 6 [mm] were verified, according to the seismic standard (García Alvarado and Lyon Gottlieb, 2013).

The developed slabs adequately resisted the solicitations with half of the original material, which implies less weight, and therefore, less cost of execution. This affects the environmental impact generated by its construction. Simultaneously, its shape (Figure 4) facilitates the installation of supports, services, or perforations, which can reduce constructive conflicts (García Alvarado and Lyon Gottlieb, 2013).

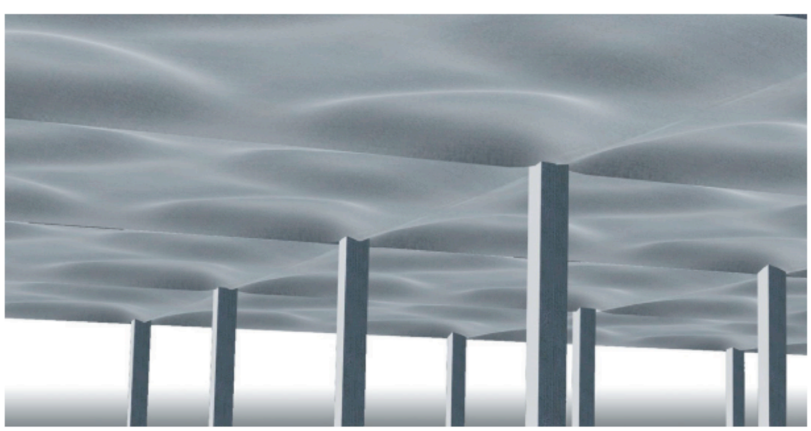


Figure 4. *Perspective view of the optimized slab (García Alvarado and Lyon Gottlieb, 2013)*

Case D: Characteristics of materials as criteria for the design of a flat lattice

Crosslinking can be made more efficient by varying parameters such as the type of profiles used, number of bars, distance between strings, among others. The combination of these variables will create a new structure with different behavior than the others. The limitation is that the designer does not have the capacity to evaluate all possible solutions generated by these changes. Gonzales, in the year 2018, developed different optimizations (Figure 5) through the integral design of metallic trusses using Rhinoceros 3D (and the Octopus and Galapagos complement) with parametric design and genetic algorithms, obtaining reticulates with a 28% saving in weight concerning to the truss obtained through the traditional trial and error method using SAP2000 (Gonzales, 2018).

In 2019, a study was developed to create a generative code to optimize the use of traditional (steel and wood) and non-traditional (bamboo) material in a flat armor. Each member was subjected only to traction and compression forces. The C-sharp complement of Grasshopper, Karamaba3D, and Galapagos was used to execute the structural calculations. It was conceptually concluded that the flat reinforcement could be optimized independently of the chosen material (steel, wood, or bamboo). This has resulted in bamboo structures that can be optimal in terms of total mass and cost, compared to those of steel. These results coincided with those that would have been expected using traditional materials or techniques (Johan et al., 2019).

One problem encountered is that the proposed generative process requires a substantial investment of time and collaboration between different disciplines, so the way the design process is perceived will have to be redesigned. This would imply that engineers, architects, programmers, and materials scientists have a new space in which each aspect of their contribution leads to the other. If the above is done without a digital collaborative platform to accommodate this workflow, generative design methods (such as the one proposed) cannot be widely implemented (Johan et al., 2019).

Additionally, the results would have to be further analyzed in a traditional structural analysis software such as SAP2000, ETABS, or other, since for the calculations, the safety factor and the characteristics of the materials were mainly used. This is not to say that a generative design method does not possess the quality to a professional standard, because due to the nature of the framework, new design and material conditions can easily be integrated to refine the performance further, allowing an exploration of structural possibilities that otherwise would have been ignored (Johan et al., 2019).

Thanks to techniques that use genetic algorithms, the design team have been able to find a greater amount of solutions compared to those that would have created the designer, which shows that the human evaluation is slower compared to these techniques (Betancourt et al., 2012).

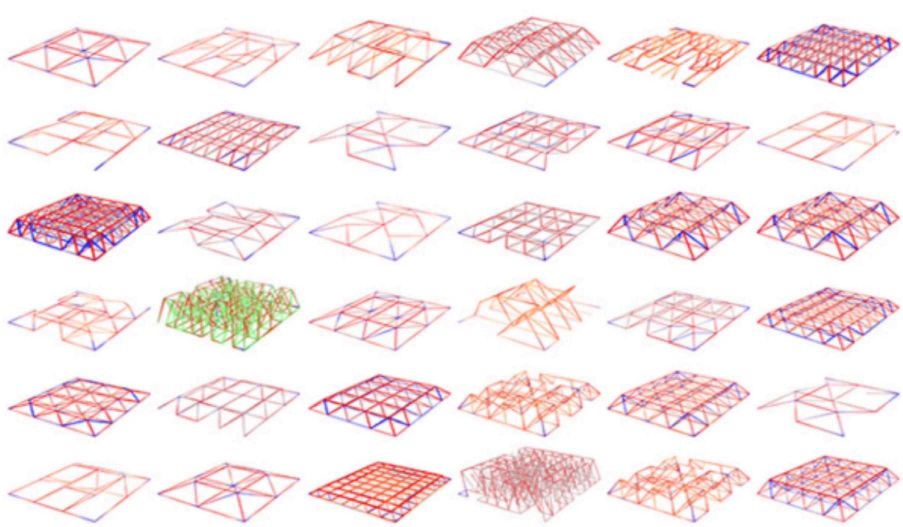


Figure 5. *Reinforcement optimization results (Johan et al., 2019)*

Case E: Material optimization for deep reinforced concrete beams

The main objective of structural optimization is to modify variable values to maximize or minimize a certain objective function and satisfy certain constraints. One type of structural optimization is topological optimization, which, as mentioned, consists of distributing the material within a volume to maximize the performance of the structure by generating designs that do not depend on the designer's criteria (Uarac et al., 2015).

Silveira and Vivan (Turney, 2020) used the generative design to optimize deep-beam reinforced concrete around variables such as cost, weight, material usage, manufacturing time, and performance. The first objective was to understand which parts can be subtracted from the original model while maintaining structural integrity. Therefore, the analysis was done using finite elements. While the concrete was being removed, steel bars had to be added as reinforcement. Then, the optimal point between both materials was sought to make the structure as economical, fast to build (with 3D printing), light, and aesthetically pleasing as possible. (Turney, 2020).

It was necessary to work with Project Refinery and Dynamo. It was observed how the beam behaved as it gradually added load to strengthen the structure in the right places. Then, for each increase in load, the algorithm analyzed which small elements could be excluded without compromising the whole set's structural behavior, as shown in (Figure 6), wherein an ascending manner, the models are losing cross-sectional area. Subsequently, ten models of the 1,000 design alternatives generated by the algorithm were physically constructed. These prototypes were tested empirically to guide the software solutions and thus combine the structural behavior with the material used (Turney, 2020).

The team believes that this method helps advance sustainable concrete construction techniques, as the process directly resulted in a 55% material saving compared to a completely humane design. After testing the possibilities for reducing material, the researchers said the next logical step is to explore better materials technology, incorporate additive manufacturing, and make the entire process even smarter (and greener). Also, they suggested exploring 3D printing since traditional formwork restricts concrete to straight lines (Turney, 2020).

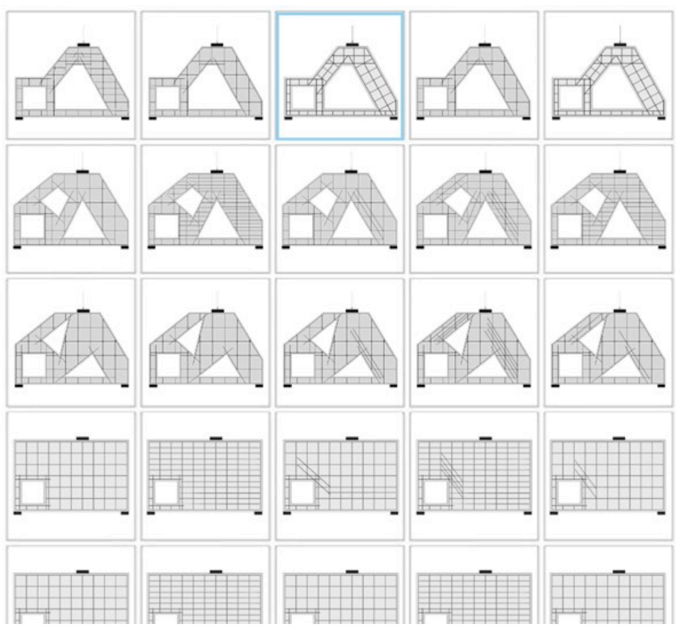


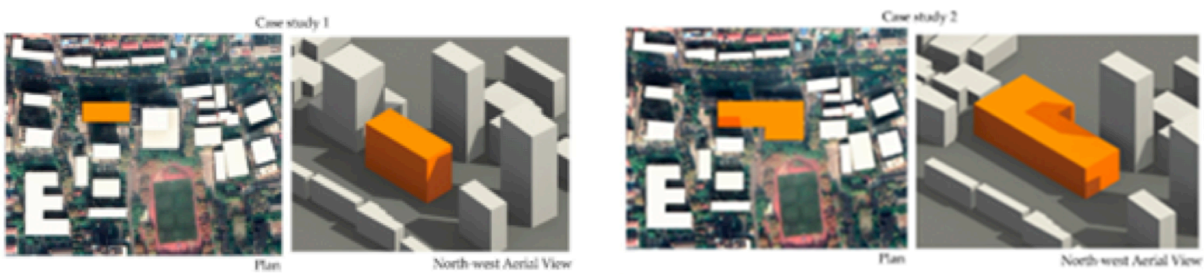
Figure 6. *Beam optimization process (Turney, 2020)*

Case F: Exterior design of buildings for natural light optimization

Although this case is more related to architecture, the next step would be to perform a structural analysis of the models, so it was considered interesting to integrate it. In this study, two buildings were presented: one of medium height and another of great elevation. These have problems in capturing natural lighting because they are surrounded by several structures of medium and high height (Figure 7). To improve the energy performance of the buildings, architects could generate, through trial and error, different exterior designs for them. However, this process would be laborious and time-consuming, and the solutions developed would be influenced by the cognitive biases of the architects (Wang et al., 2019).

The annual energy consumption per lighting was calculated and improved using the DIVA simulation tool (based on Radiance) in Rhino-Grasshopper. The effect of the optimization on daylight is significant as it improved on average by 96% compared to the reference set. If the optimization results were allowed more geometric freedom such as torsion, rotation, and inclination (and not only orthogonal shapes), the results could be improved even more. The problem is that the model already has a large number of optimization parameters built-in, so adding others could be ineffective, as this could prevent other high-performance solutions from being found (Wang et al., 2019).

Instead, it is recommended to divide the optimization process into two parts. In the first stage, different external forms of the building can be explored, while in the second, it is possible to choose a small number of models with desired architectural characteristics and apply the optimization process again to develop even more specific solutions (Wang et al., 2019). If the procedures and software of generative design become friendly to designers, this technique will revolutionize the way architects create their models since there is a growing need to reconcile different and contradictory objectives in order to generate more sustainable buildings (Touloupaki and Theodosiou, 2017).



(**a**) (**b**)

Figure 7. Plan and an aerial view of the buildings; in orange, the structure to be optimized is shown (Wang et al., 2019) (**a**) High rise building; (**b**) Medium height building.

Case G: Structural analysis of non-conventional facades

This case, like the F case, is more related to architecture but leaves the need to make a structural analysis of the result obtained. The generative design in this area will help to automate parts of the design process to generate more efficient solutions, reduce costs, to optimize, exploring more alternatives (Singh and Gu, 2012).

In this research, the second tower's supporting facade (designed but not built) of the Santamaría offices in Santiago de Chile was redesigned. After modeling the entire building in Revit, Rhinoceros with Grasshopper was used to vary the geometry of the total volume and Digital Project to define the adaptive components of the facade (García Alvarado and Lyon Gottlieb, 2013).

In this case, for the generative design implementation, architects and structural engineers were involved in defining solutions from different criteria, such as resistance, displacements, minimum and maximum dimensions of construction elements, interior lighting conditions, and opening of relevant views. The tower is structured mainly through the core, although each of the four facades has 14 columns that discharge vertically. Given the seismicity of

Chile, horizontal forces were incorporated in different directions, which can be absorbed (in part) by the elements of that facade (García Alvarado and Lyon Gottlieb, 2013).

The analysis considered the solar exposure of the facades, construction criteria for prefabricated reinforced concrete formwork, and various digital and physical models with rapid prototyping to review their architectural expression. During the exercise, the most efficient ways were sought to reduce the material used in order to provide greater resistance in the building's façade plans, to control its solar exposure (and therefore, the energy consumption necessary for its cooling), and to modernize its architectural expressiveness; thus, the structure was transformed from left to right in (Figure 8). It is important to mention that the results obtained must be verified by traditional analyses that allow validating the compliance with current standards and also reviewing their execution (García Alvarado and Lyon Gottlieb, 2013).

As environmental concerns and the responsibility of the AEC industry for environmental pollution increase, solutions based on designers' experience may not be sufficient to reconcile the complexity of the parameters to be evaluated (Cavieres, 2007). Finally, the computational tools and the generative process have been able to generate unexpected forms, stimulating the creativity of designers and engineers (Betancourt et al., 2012).

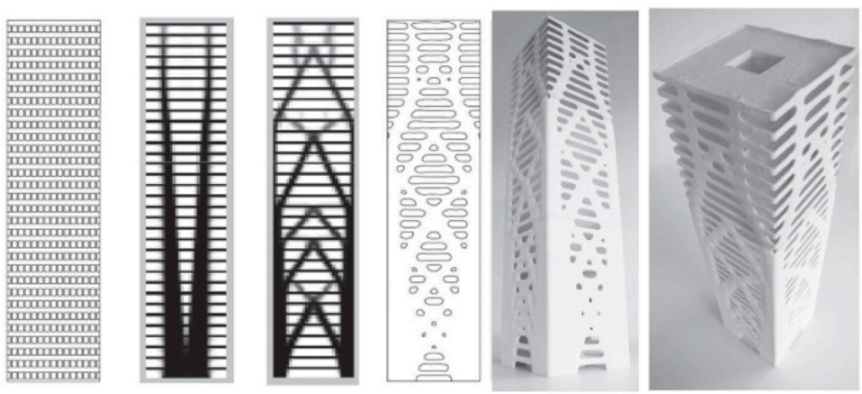


Figure 8. *Topological optimization of the building facade in height and 3D prototyping (García Alvarado and Lyon Gottlieb, 2013)*

Synthesis of case studies

(Table 4) is presented below with a summary of the problems that were attempted to be solved in each case, the types of parameters used (according to (Table 3)), the software(s) used, and the results obtained, along with their respective limitations, and in some cases, the recommendations given by the researchers for future studies.

Table 4. *Case Summary*

Variable/ Case	***A***	***B***	***C***	***D***	***E***	***F***	***G***
Problem	*Lateral stabilization of a building by modifying core characteristics*	*Reduce materials for building R.C beams*	*Reduce carbon consumption in slabs*	*Designing reinforcements from materials*	*Reducing material for deep R.C. beams*	*Low natural lighting*	*Optimize between sun exposure resistance*
Main parameters	*GP: Overall dimensions or proportions*	*LP: Response to analysis values*	*PP: Material properties*	*PP: Material properties PE: Material properties*	*LP: Response to analysis values*	*EP: Climate data and site dimensions*	*EP: Climate Data*
Software	*Packhunt.io, Viktor.ai, and "DynamoRFEM" (with Refinery).*	*MatLab*	*MatLab*	*Grasshopper with C-shaper y Karamba3D*	*Project Refinery and Dynamo*	*Rhino - Grasshoper and DIVA*	*Revit, Rhinoceros with Grasshopper and Digital Project*
Results	*Saving design time in previous stages*	*Cost reduction between 40% and 52% of CO_2 emissions between 39% and 51% per beam*	*Slabs resist the required loads with half of the original material*	*Bamboo structures are comparable to steel*	*55% material savings compared to a traditional design*	*96% savings in energy consumption*	*See Figure 8 (right)*
Limitations and/or recommendations	*Lack of linking structural data to costs*	*It requires 3D printing for its construction. It is suggested to take this methodology to a complete structure*	*The form serves to reduce construction conflicts*	*Requires large initial investment of time, human resources and verify results with SAP2000 or ETABS*	*Explore materials technology, additive manufacturing and 3D printing*	*Not all parameters were added because they would make the model inefficient*	*Results should be verified by traditional analyses that allow validation of compliance with current standards and also review their execution*

3.2 Civil engineers' perception of generative design

Of the 52 valid surveys, 4% had less than two years of professional experience in the design of structures, 56% had more than ten years (Figure 9), and 40% had between 2 and 10 years. Looking at the type of projects in which they work, 37 of them work in "Residential and office building", 25 in "Industrial works", 12 in "Road works" and "Non-residential building" respectively. Regarding the generative design, 65% admit to not knowing or having little knowledge of it, 25% declare to know what it is, and 8% have used it.

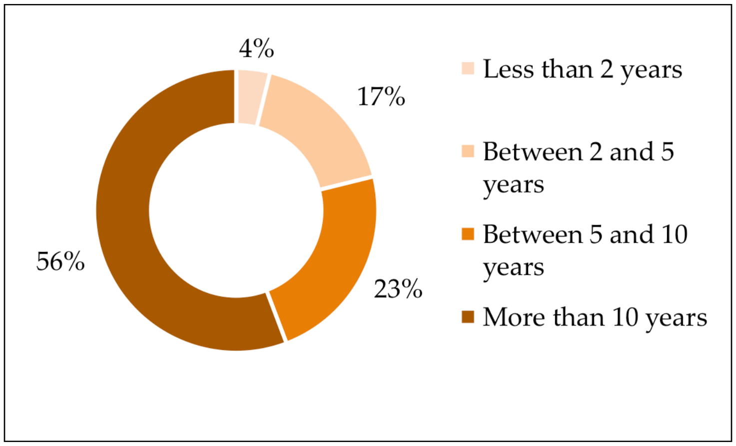


Figure 9. *Professional experience in the design of structures*

Regarding the aspects that would improve with generative design, 37 professionals indicated that they would use this process to optimize resources, 26 to optimize design times, 22 to have more design options, and 9 to save energy. Concerning the question about which structural design problems could be optimized through generative design since it is open-ended, the answers were grouped into the five topics shown in (Figure 10). For the idea of pre-design (the most discussed), it was observed that the key concept was to automate the pre-design process to generate different options that integrate costs quickly. The second bar of the graph talks about generating non-traditional designs, but more efficient than those currently used and/or considering new building structures. The fourth classification states that the professionals surveyed would like to optimize structural elements such as beams, columns, and slabs to reduce the amount of material used and, consequently, the cost and pollution. The fifth category observed in the responses was to use generative design to optimize steel rebar and/or restrict options in the type of connections of the same material, given the iterative nature of its design. Finally, the concept "Others" gathered the responses that were not aligned with the others and that had low frequency (less or equal to 2), such as using the generative design for foundation sizing, design of critical reinforced concrete zones, "determine redistribution of efforts and deformations in the structure considering the response of the foundation", design based on threat, among others.

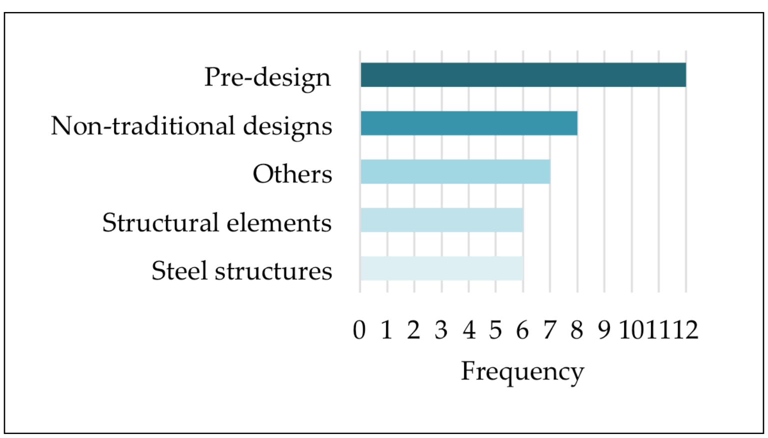


Figure 10. *Professional experience in the design of structures*

The opinion of the professionals surveyed who have not used generative design regarding the feasibility of employing this process in civil engineering is shown in (Figure 11). These results show that only 2% believe it is "not at all feasible", while 21% consider it "not very feasible"; on the other hand, 67% see it as "feasible" and 10% as "very feasible".

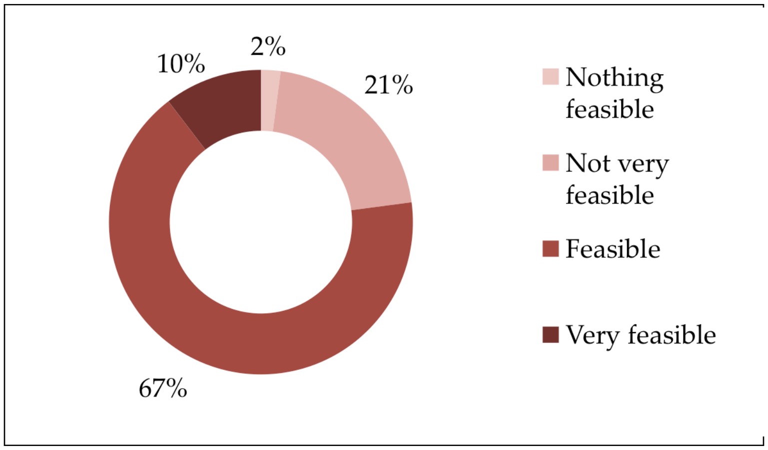


Figure 11. *Feasibility of applying the GD according to civil engineers*

Some of the main justifications offered to support this process's feasibility were the fact that it responds to the basic iterative principle of structural design and the great help it can be in pre-design stages, especially for aesthetically innovative structures. On the contrary, as limitations to implementing the generative design, the cost and availability of adequate software and cultural issues associated with following traditional design procedures were made explicit. At the same time, as aspects to consider emerged to consider the coordination with architecture and / or the client to define the parameters (and their ranges) and question what scale is to be implemented (small and medium or large enterprises).

However, the civil engineers who have used this process (4 professionals) have used it to define optimal structural plants, define crane locations, design bridges considering different support and load restrictions, design mechanical parts to satisfy resistance conditions, and natural frequency control design of non-traditional structures. This process's main benefits are the multiple design alternatives available since this allows considering options that were not planned and that are known beforehand to be structurally efficient and provide material savings. Besides, with generative design, the design's sensitivity to the change of the parameters that shape it can be more clearly appreciated, and through this process can be linked. Concerning the obstacles to implementation, there is a complication in defining the design restrictions and their interdependence, the cost of commercial software for programming the code, in addition to the time required for its development, and finally, the time for evaluating the suitability of the model.

It should also be noted that 75% of the respondents who have used the GD believe it is "feasible" to use it in their professional practice, while 25% believe it is "very feasible". Going deeper into the reasons given, the possibility of having various alternatives for decision making arises again, although with this, the need to learn to model the design processes themselves also appears. Along with the above, it is evident that there is a need for computational speed that allows a quick evaluation of each possible solution (in addition to the software itself).
Finally, possible applications of this process are the optimal design of reinforcements and definition of their sections, urbanization problems (related to smart cities), and design by capacity of structures based on walls and space distribution situations in general.

4. Conclusions

The preceding analysis indicates the incipient but promising use of the generative design in structural engineering, through the optimization of structural elements such as beams, slabs, and trusses, where the most commonly used software for this purpose is REVIT with its Dynamo and Refinery complements, and Grasshoper with its Rhinoceros complement. It is worth mentioning that the first of these is a common environment for civil *engineers since it is a program used by the BIM methodology. The use of the generative design in civil engineering is therefore proposed as a tool for building structures that can meet the same conditions as the current ones, but with less material, which translates directly into money savings for companies and, more importantly, a reduction in pollution caused by the generation, transport, and placement of this extra material.*

In this perspective, it is also important to observe the varied experiences that architecture has had with this process, and that point firstly towards saving the energy expense produced by the construction and operation of the buildings and; furthermore, to deliver different design options in an expeditious manner considering the parameters and input variables of the code. It is here where the need for collaborative work throughout the AIC industry becomes evident, from the beginning of each project; where the generative design helps to create pre-design options quickly, considering in the first stage, the most important parameters such as the solar exposure of the structure, spatial limitations given by regulations such as the ground level, land occupation coefficient, and constructability coefficient. The civil engineer could then optimize the structural elements of this design to consider configurations that he might not have foreseen following the classic trial and error design method. Finally, the generative design can help estimate the best way to position the cranes for constructing the model created above.

This means that generative design is easily compatible with structural engineering processes since the latter is based mostly on iterative systems that can be easily covered by the former. In turn, it allows the use of alternatives not considered by the designer but that is highly efficient. Regarding the survey results, most of the civil engineers surveyed do not know or have not worked with generative design, which confirms the initial motivation of this work, which is the need to make this process known in the industry, showing both its advantages and limitations.

A difficulty in the implementation of generative design is the fact of having to restructure the design process since it is not based on directly looking for solutions but on teaching the software to design, which in turn is beneficial because, in this development, one must have clarity of the parameters and restrictions that shape the design, which makes this process less dependent on the experience of the designer and would make explicit the particular conditions of each project. This does not mean that the engineer will not be necessary, but on the contrary, he must develop the ability to decide which is the best design within the options provided by the code. Another limitation for its use, in which both professionals who have used this process and those who have not, agree, is the cost of the software, which is expected to be less relevant shortly since programs such as REVIT (version 2021) already include a generative design section, which suggests that this tool will soon be integrated into the software used in the industry.

One aspect to consider is that, given the actuality of this topic, some studies presented as generative design are not so clearly identified and are a mixture between it and parametric design and/or genetic algorithms. For this reason, it is evaluated on a case-by-case basis according to the definition given in the introduction to this document. In addition, other uses of generative design in structural engineering not contemplated here may have been disclosed in the course of the development and publication of this document.

As future lines of research, it is suggested to investigate the use of the generative design in other areas of civil engineering and the AEC industry in order to extend its benefits to this entire field and to be able to generate collaborative projects that connect with some of the principles of other innovations, such as the BIM methodology. Finally, it proposes creating, testing, and implementing its own codes that solve specific industry problems to directly show its benefits.

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