Generative Design Method (GDM) – A State of Art

Rajneesh Jaiswal¹, Vandana Agrawal²
¹Master’s student, CAD&M, Dept. of Mechanical Engineering, Motilal Nehru National Institute of Technology (MNNIT) Allahabad, India
²Assistant Professor, Dept. of Mechanical Engineering, Motilal Nehru National Institute of Technology (MNNIT) Allahabad, India

Email: jaiswalrajneesh60@gmail.com, vandana@mnnit.ac.in

Abstract. This paper presents the review of generative design method (GDM). The main aim of generative design system is to create new design that produces number of feasible distinct design with the help of computing power and manufacturing capability. A generative design process has mainly three important components, which are a structured design framework, a method of generating dissimilarity, and a way of determining preferable outcomes. The aim of this paper is to review the different generative design method (GDM), its role in the product design and development especially in conceptual design phase, which is a time consuming, and complex design process, and to assist designer in creating innovative design of existing design. Based on the literature survey, the various classification involved in generative design method, and its applications in different fields have been discussed.

1. Introduction
In modern days, the industrial/engineering products design is important task for designer according to the increasing demand of customer not only based on functional performance but also the appearance of the products in daily life. Therefore, in the initial product design process (i.e. also known as conceptual design stage) to explore alternative design by hand sketching is time-consuming process. Designer may not be able to predict all possible variation of shapes of the product and in this stage use of computer-aided design (i.e. CAD) is very limited; it is mainly utilized in later stage to analyze, validate and fabricate the design [1]. Here in the modern era, there are so many advancement in the field of optimization techniques, design simulation, parametric design technique, and extensive application of computer programming. Therefore, it allows design engineer a new way of exploring design as compared to old days [2]. Therefore, a generative design method came in to existence to provide distinct design/shape of the product based on the consumer preferences.

In any product development process, conceptual design stage is an important phase in an engineering design of product. This phase is complex one and large amount of time is required when we talk about the appearance of the product based on consumer needs for generating number of designs. Therefore, based on design requirements (i.e. design parameters, its range and geometric constraints) of the product, it is important to have system that should provide number of distinct optimal design/shapes in design space and the method is known as generative design method.
2. Applications
Generative design method was initially used in the area of Architectural design but it is now used in various applications, like industrial design, jewelry design, consumer product design etc. Its few applications and advantages are given below.

- It has application in conceptual or initial design phase as it provides number of design shapes. For example it can be used in ornament industry mainly in jewellery design to generate number of designs with less effort.
- It can be integrated with Design for manufacturing (DFM) software to ensure manufacturability.
- It enables the design engineer to explore multiple ideas and make better-informed decision during early design stage.
- It reduces the process time, as designer has to explore the different design by like traditional method like 2D drawing and hand sketching etc.

Due to its wide applications, various generative design methods have been proposed. In the present paper, a state of art of it is presented for the same. The paper is organized as follows: section 3 provides the literature review related to generative design method, and its classification. Section 4 gives the applications of different generative design techniques, Section 5 provides comparison of different technique and finally section 6 gives the conclusion.

3. Literature Review
A large volume of literature is available explaining the generative design method (GDM), its classification and applications in the various fields. In this paper, a review of literature has been carried out related to engineering applications. Here sub-section 3.1 gives the definition of generative design method and its major components.

3.1. Generative Design Method (GDM)
Sometimes, product design phase is critical and time-consuming process, which create burden on the designer to explore innovative design a case for example there may be when appearance is valuable to customer. In such cases, generative design method can be utilized for generating 2D profile as well as 3D CAD models.

Frazer [3] pioneered the concept of “generative design” in year 1970’s. The main aim of generative design system is to create new design process that produces number of feasible distinct design with the help of computing power and manufacturing capability as given by Shea [4]. The number of design alternatives for the products may be in the form of 2D sketch, image, drawings or 3D parametric CAD models. Generative design process contains three major components (1) A structured design framework, (2) A method of generating dissimilarity, (3) A way of determining preferable outcomes.

3.2. Classification of GDM
The generative design method can be classified in five different categories based on the literature survey, which are constrained parametric search strategy [6,29], evolutionary algorithm [10-12,26,30], iterated local search (ILS) [7-9], shape grammar [13,15,16], and topology optimization tool [1,27,28]. Each of the method is described briefly in the following subsection as given below.

3.2.1. GDM based on constrained parametric search. Sivam Krish [6] proposed a generative design method to explore various design in conceptual design phase. This method is totally designer driven method and it does not limit imagination of designer, which is the major advantage of this technique. Overall proposed method can be understood from flowchart of steps involved in generative design process as shown in figure 1. Here the CAD based generative design system is presented where genetic model and geometric constraints replace the algorithm and source code respectively. Due to this reason, this proposed generative design system is more designer centric.
Major limitation of proposed GDM is that this is an exhaustive search method, as it requires multiple genotype to explore large design space because single genotype cannot cover entire design space.

One more method has been proposed by Bentley [29] based on this classification which is known as genetic algorithm designer (GADES) method which utilizes the above concept and genetic algorithm technique.

![Flowchart of Generative design process.](image)

3.2.2. GDM based on iterated local search (ILS). Khan et al. [7] proposed a sampling technique, which is an extended version of Latin hypercube sampling (ELHS) to explore the design alternative of the CAD models in constrained and high dimensional design space. In the ELHS technique, number of trials is same as number of interval and in any trail; only one design is taken from each sub-space based on LH-rule [7]. Among all designs (feasible and infeasible both), a feasible design is considered based on enumeration in each trial and one who provide the minimum cost value is selected. To generate distinct designs, a similarity constraint (i.e. similarity threshold) is utilized based on Euclidian distance. A candidate solution is selected based on one who has the minimum cost value and satisfy the LH-rule [7].

There is a limitation of this sampling technique that the designs obtained do not always provide the space filling property as it is dependent on input design.

Gunpinar et al. [8] proposed a technique, which is known as shape sampling approach to explore the various shape in the constraint shape space within pre-defined product specification. This technique is based on generative design method that utilizes particle tracing (PT) algorithm [23,24]. Here sampling quality is computed based on two factors which are space filling and computation time so it requires that a sample should have good space filling property and less computation time.

Dogan et al. [9] proposed a generative sampling system to generate number of 2D profiles based on given constraints within pre-defined design space. It proposes for 2D problem (i.e. image as input) which utilizes a sampling algorithm by programming for design space. Number of different samples are
generated by minimizing Audze-Eglais potential energy [14] for having uniform distribution of samples. Distinct samples are generated while maintaining curve degree, continuity and concavity property. Samples are produced by modifying the profile curve and the sampling algorithm finds the ones within the bounds specified by user-provided similarity thresholds satisfying the conditions and constraints.

3.2.3. **GDM based on evolutionary optimization algorithm.** Khan et al. [10] proposed a sampling-TLBO technique (S-TLBO), which is generative design technique to generate all possible design option for CAD models in constrained and unconstrained design space within the pre-defined design constraints, so that designer or customer can think about all possible designs. This S-TLBO technique can be utilized for high dimensional problem with good space filling property and provides proper sampling within highly irregular environment of infeasible designs. S-TLBO technique is an extension of basic TLBO (Teaching learning based optimization i.e. evolutionary optimization technique) [22] from single optimal solution to multi-optimal solution. TLBO algorithm utilizes the philosophy of teaching and learning in the class, which is a popular among meta-heuristics optimization algorithms such as genetic algorithm (GA) [18], particle swarm optimization (PSO) [19], artificial bee colony (ABC) [20] and covariance matrix adaptation evolution strategy (CMA-ES) [21] due to effective performance and simplicity in use.

Khan et al. [11] proposed a generative design technique, which is known as space-filling-GDT (Sf-GDT) to generate optimal design alternative for CAD models in design space within pre-defined design constraints. In this work, Jaya algorithm [17] which is utilized for effective search strategy and advantage of using this algorithm that does not require any tuning of specific parameter as in the case of genetic algorithm. To produce distinct designs, a weighted grid method is integrated with proposed GDT. This proposed method is also able to explore hybrid design space, which consists both continuous and discrete parameters. In this research paper, an example of ceiling lamp is taken while considering both criteria space filling and non-collapsing feature to produce distinct optimal designs as shown in figure 2.

![Figure 2](image_url)

**Figure 2.** Shapes generation of ceiling lamp of three-design parameter by Sf-GDT. (a) Input parametric CAD model. (b) Generated 3D CAD models.

Moriguchi et al. [12] proposed a generative design technique which is also known as SSA design sampler (SSA-DS) to generate the number of creative designs in the pre-determined design space. This is automatic search technique based on spatial simulated annealing (SSA) [25] to produce N number of designs in constrained/unconstrained design space. Here uniform distribution of generated designs (i.e. space filling criteria) is achieved by minimizing Audze-Eglais potential energy [14]. Several other research work has been carried out using this approach as [26, 30].

3.2.4. **GDM based on shape grammar.** Kielarova et al. [13] proposed a generative design system, which utilizes the shape grammar based GDT and a set of shape rules to explore various design and these set of shape rules are based on shape transformation rule. The proposed method was applied on jewellery
ring design. However, this technique has major drawback that it requires an expert for defining set of transformation steps for each object separately.

Another approach using the concept of shape grammar and evolutionary algorithm by Kieralova et al. [15]. This method was applied on jewellery design of ring. Pugliese et al. [16] proposed a method, which is based on shape grammar and utilizes to extract the model of Harley-Davidson brand motorcycle.

3.2.5. **GDM based on topology optimization tool.** Kazi et al. [1] proposed a generative design tool (i.e. known as DreamsSketch tool) which is based on topology optimization to explore the various shapes using 2D digital sketching skills. Further topology optimization is done to get feasible optimized shape. The algorithm was applied on connecting rod using Autodesk Inventor. This topology optimization tool is based on minimization of stiffness while fixing the volume to certain value or fraction and minimization of weight under stress or displacement as constraints. Several other research work has been carried out using this approach [27, 28].

4. **Applications of Different techniques**
This section explains in brief the area where the various generative design method can be applied for analysis of different shapes of any product within certain defined constraint in initial design phase of product development process.

Here constrained parametric search based GDM is a designer driven technique to explore the solution space (or design space) to obtain number of different design by utilizing genotype. This proposed method is based on exhaustive search strategy due to maximum involvement of design engineer/designer and application is limited in daily usable products due to need of more time and difficult for normal person other than designer.

An evolutionary algorithm based GDM is automatic search strategy to explore entire design space within pre-defined customer specifications. This proposed generative design method can be utilized by a customer or designer easily and experts are not required. This technique uses evolutionary optimization algorithm such as genetic algorithm (GA) [18], Spatial simulated annealing (SSA) technique [25], teaching learning based optimization (TLBO) [22], Jaya algorithm [17], particle tracing (PT) algorithm [23,24] etc.

In shape grammar based GDM, shape grammar is used to create generative design technique for design exploration based on shape grammar rules. However, implementing shape grammar is still a problem for generalized problems in the present days. So fixed shape structure is considered via analysis of simple shape grammar for consequences analysis. Here it is proved that capability of shape grammar is limited by choosing finite fixed structure. Shape grammar is generally used for 2D design space and rarely used for 3D design exploration problems.

In topology optimization tool [5] based GDM, which has input as problem definition and output as a single or number of optimal solutions. This GDM utilizes mathematical methods, which optimally distribute the material within a pre-known design space. Its main objective function is to maximize or minimize the stiffness and minimize the weight while considering the volume fixed and stress as constraints. In the modern day, number of software are currently used by various industries on the large scale like Altair’s OptiStrut, efiForm, and Abaqus 6.14 etc.

5. **Comparison of Different techniques**
As compared to evolutionary algorithm like spatial simulated annealing (SSA) [12], Particle tracing [8] technique based GDM (i.e. iterated local search technique) provides better space filling property and shorter computation time. One major limitation of PT algorithm is that it does not always guarantee to obtain feasible shape in shape space and distribution of infeasible region is highly irregular. This above problem has been removed in evolutionary algorithm based GDM e.g. Jaya algorithm, TLBO based GDM etc.
As compared to shape grammar, constrained parametric search based GDM does not need any special external rules and grammar encoding. However, this constrained parametric search cannot be utilized for the engineering problems, which are computable, and correlation between problem and solution space is possible as compared to evolutionary algorithm based GDM technique.

Topology optimization tool [5] based GDM provides different design based on material removal from the object while minimizing stiffness, keeping volume fixed, and other constraints criteria as compared to other method.

There are also other methods [31-34] Which provides number of different shapes as compared to generative design method but generative design method have advantage of utilizing non collapsing and space filling criteria to provide distinct and optimal designs.

6. Conclusion
This paper proposes a review on generative design techniques, their advantages, limitations, and applications. GDM is mainly used for generating number of designs and the design best suited according to user is selected. GDM is mainly classified in to five categories which are based on (1) Constrained parametric search strategy, (2) Evolutionary optimization algorithm like GA, ABC, SSA, CMA-ES, Jaya algorithm, TLBO technique etc., (3) Iterated local search technique, (4) Shape grammar rule, (5) Topology optimization tool.

Generative design method provides number of distinct shape without any proper model set and also generate design alternatives considering non-collapsing and space filling property as compared to other method of shape exploration.

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References
[1] Kazi R H, Grossman T, Cheong H, Hashemi A and Fitzmaurice G 2017 Dreamsketch: Early stage 3d design explorations with sketching and generative design Proc. of the 30th Annual ACM Symp. on User Interface Software and Technol. (UIST), ACM, (New York: Association for Computing Machinery) pp 401-14.
[2] Umetani N, Igarashi T and Mitra N J 2012 Guided exploration of physically valid shapes for furniture design ACM Trans. Graph. 31 pp 1-86.
[3] Frazer J H 2002 Creative design and the generative evolutionary paradigm Bentley Creative evolutionary systems ed P J and Corne D W (San Francisco:Morgan Kaufmann) pp 253-74.
[4] Shea K, Aish R and Gourtovaia M 2005 Towards integrated performance-driven generative design tools Autom. Constr. 14 pp 253–64.
[5] Nana A, Cuilliere J C and Francois V 2016 Towards adaptive topology optimization Adv. Eng. Softw. 100 pp 290–307.
[6] Krish S 2011 A practical generative design method Comput. Aided Des. 43 pp 88-100.
[7] Khan S and Gunpinar E 2017 An extended Latin hypercube sampling approach for CAD model generation Anadolu University Journal of Science and Technology A- Applied Sciences and Engineering 18 pp 301-14.
[8] Gunpinar E and Gunpinar S 2018 A shape sampling technique via particle tracing for CAD models Graph. Models 96 pp 11–29.
[9] Dogan K M, Suzuki H, Gunpinar E and Kim M 2019 A generative sampling system for profile designs with shape constraints and user evaluation Comput. Aided Des. 111 pp 93-112.
[10] Khan S and Gunpinar E 2018 Sampling CAD models via an extended teaching–learning-based optimization technique Comput. Aided Des. 100 pp 52–67.
[11] Khan S and Awan MJ 2018 A generative design technique for exploring shape variations Adv.
Eng. Inform. 38 pp 712–24.

[12] Khan S, Gunpinar E and Moriguchi M 2017 Customer-centered design sampling for cad products using spatial simulated annealing Proc. of CAD’17 (Okayama) pp 100-03.

[13] Kieralova S W, Pradupphongphet P and Bohez E L J 2013 An Approach of Generative Design System: Jewelry Design Application 2013 IEEE Int. Conf. on Industrial Engineering and Engineering Management (Bangkok:IEEE) pp 1329–33.

[14] Audze P and Egliais V 1977 New approach for planning out of experiments Problems of Dynamics and Strengths 35 pp 104-7.

[15] Kieralova S W, Pradupphongphet P and Bohez E L J 2015 New interactive-generative design system: hybrid of shape grammar and evolutionary design – an application of jewellery design Int. Conf. in Swarm Intelligence ICSI 2015: Advances in Swarm and Computational Intelligence pp 302-13.

[16] Pugliese M J and Cagan J 2002 Capturing a rebel: modelling the Harley-Davidson brand through a motorcycle shape grammar Res. Eng. Des. 13 pp 139-56.

[17] Rao R V and Waghmare G 2017 A new optimization algorithm for solving complex constrained design optimization problems Eng. Optim. 49(1) pp 60–83.

[18] Halldurai L, Madhubala T and Rajalakshmi R 2016 A Study on Genetic Algorithm and its Applications Int. J. Comput. Sci. Eng. 4(10) pp 139-43.

[19] Poli R, Kennedy J and Blackwell T 2007 Particle swarm optimization: An overview Swarm Intelligence 1(1) pp 33-57.

[20] Karaboga D and Basturk B 2008 On the performance of artificial bee colony (ABC) algorithm Appl. Soft Comput. 8(1) pp 687-97.

[21] Igel C, Hansen N and Roth S 2007 Covariance matrix adaptation for multi-objective optimization Evol. Comput. 15(1) pp 1-28.

[22] Yu K, Wang X and Wang Z 2016 Constrained optimization based on improved teaching–learning-based optimization algorithm Inf. Sci. 352 pp 61-78.

[23] Gunpinar E, Suzuki H, Ohtake Y and Moriguchi M 2013 Generation of bi-monotone patches from quadrilateral mesh for reverse engineering Comput. Aided Des. 45(2) pp 440–50.

[24] Gunpinar E, Moriguchi M, Suzuki H and Ohtake Y 2014 Feature-aware partitions from motorcycle graph Comput. Aided Des. 47 pp 85–95.

[25] Alrefaei M H and Diabat A H 2009 A simulated annealing technique for multi-objective simulation optimization Appl. Math. Comput. 215(8) pp 3029–35.

[26] Chen B, Pan Y, Wang J, Fu Z, Zeng Z, Zhou Y and Zhang Y 2013 Even sampling designs generation by efficient spatial simulated annealing Math. Comput. Model. 58(3-4) pp 670–6.

[27] Hoosmand A and Campbell M I 2016 Truss layout design and optimization using a generative synthesis approach Comput. struct. 163 pp 1-28.

[28] Sangeun O, Yongsu J, Seongsin K, Ikin L and Namwoo K 2018 Deep Generative Design: Integration of Topology Optimization and Generative Models Int. Design Eng. Technical Conf. & Computers and Information in Eng. Conf. (IDETC/CIE) (Quebec City:ASME).

[29] Bentley P J 1999 From coffee tables to hospitals: generic evolutionary design Evolutionary design by computers, ed Bentley P J (San Francisco: Morgan Kaufmann) pp 405-23.

[30] Caladas L 2006 GENE_ARCH: an evolution-based generative design system for sustainable architecture Lect. Notes Comput. Sci. 4200 p 109.

[31] Kalogerasikis E, Chaudhuri S, Koller D and Koltun V 2012 A probabilistic model for component-based shape synthesis ACM Trans. Graph. 55 pp 1–11.

[32] Kleiman Y, Fish N, Lanir J and Cohen-Or D 2013 Dynamic maps for exploring and browsing shapes Proc. of the 11th Eurographics /ACMSIGGRAPH Symp. on Geometry Processing (Goslar:Eurographics Association) pp 187–96.

[33] Averkiou M, Kim V G, Zheng Y and Mitra N J 2014 Shapesynth: Parameterizing model collections for coupled shape exploration and synthesis Comput. Graph. Forum 33(2) pp 125–34.
[34] Schulz A, Xu J, Zhu B, Zheng C, Grinspun E and Wojciech M 2017 Interactive design space exploration and optimization for cad models,” ACM Trans. Graph 36(4) 157.