ARTICLE

Precision Engineering Design Process for Optimal Design Based on Engineering Sciences

Amir Javidinejad*

Boeing Global Services-Engineering Modifications and Maintenance Department, Boeing Company, 4000 N Lakewood Blvd, Long Beach, CA 90846, USA

ARTICLE INFO	ABSTRACT
	Concepts of precision engineering design process for optimal design where engineering sciences contribute in the successful good design are elaborated in this paper. Scientific theory and practicality are discussed in this paper. Factors necessary for a complete product or systems design are detailed and application of mathematical design optimization in producing a good design are shown. Many applicable engineering design examples are itemized to show relevancy of the optimal design theory to engineering design. Future trends of optimal design with respect to the 4th industrial revolution of digitization are presented. Paper sets to elaborate that most of the engineering and scientific design problems can be optimized to a good design based on many new/advanced optimization techniques.

1. Introduction

To start with, it is essential to understand the classical theories and definitions of "engineering design" and "engineering design process" before moving into the discussion of advanced topics of optimal design based on engineering sciences. According to ABET, engineering design is a process of developing a functional system, component or process to satisfy a series of desired needs and specifications within a defined set of constraints (ABET [1]). Furthermore, ABET states that engineering design "is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions. Engineering design involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade- offs, for the purpose of obtaining a high-quality solution under the given circumstances."

Moving forward to the concept of engineering design process, the process itself is defined by series of process stages known as *research, conceptualization, feasibility assessment, establishing design requirements, preliminary design, detailed design, production planning and tool design, and production* Ertas, A., Jones, J. [2]. Thus, that herby the classical engineering design and engineering design process are defined and clearly made obvious to an engineer; it is necessary to also explore optimal design concept as a fundamental tool. The simplest definition of optimal design is the final set of all known iterative and

Corresponding Author:
Amir Javidinejad,
Boeing Global Services-Engineering Modifications and Maintenance Department, Boeing Company, 4000 N Lakewood Blvd, Long Beach, CA 90846, USA;
Email: Amir.Javidinejad@gmail.com

experimental designs that have reached a meaningful statistical definition of best choice that represents the specifications and satisfies the initial and final design constraints.

An optimal design ("Good Design") by definition and by virtue of results is a design where technological factors, user factors and economic feasibility factors come together and produce a complete system or component. Altringer and Habbal [3] indicate that technological factors are based on the engineering, science and math foundations with ergonomics and manufacturing being the common factor with user factors and economic factors, respectively. User factors are based on sociology, psychology and anthropology criteria with marketing being the common factor with the economic factors. Economic feasibility factors are based on the business, market and government criteria. These factors as a whole summarize the requirements for optimal design concepts at a high level that set a preliminary engineering mindset needed for carrying a design process. Refer to Figure 1 for an illustrative purpose of the optimal good design concept.

Other relevant factors that also contribute into a good design are implementation of design thinking with systems thinking for engineering design, Melissa T. Greene, Richard Gonzalez, Panos Y. Papalambros and Anna-Maria McGowan [4]. Melissa Greene [4] elaborate that until recently design thinking and system thinking engineering design were not complimentary to each other. This work by Greene et al. indicated that, in the past, design thinking methods concentrated on industrial design and product development while system thinking engineering design

methods was used in professional system engineering practice and large scale, complex designs. This literature [4] indicated that classical design thinking theory, originally introduced by Herbert Simon in 1969, consisted of seven stages for a product design; defining the problem, researching, ideating, prototyping and choosing a solution, implementing the solution and learning. Further, it was indicated by Greene et al., that system thinking engineering design has roots mainly in the operations research where as traditional systems engineering and management science along with dynamic systems, Forrester [5] and General Systems Theory, L. Von Bertalanffy [6] define the system engineering theory. The combination of these two schools of thinking is a modern-day concept for design process where design thinking is required for successful design of products and systems considering all three factors of "good design"; which are technological factors, user factors and economic feasibility factors.

Having established the high-level requirements, scientifically these requirements can be translated into numerical methods established in engineering science theory and practice. Use of numerical methods guarantees the iterations necessary for optimal design approach. CAD and Simulation Tool utilization makes the application of engineering sciences into the design process very lucrative. Good representation of such optimization examples is the structural topology optimizations introduced into civil structural design processes, Georgios Kazakis, Ioannis Kanellopoulos, Stefanos Sotiropoulos and Nikos D. Largaros [7].

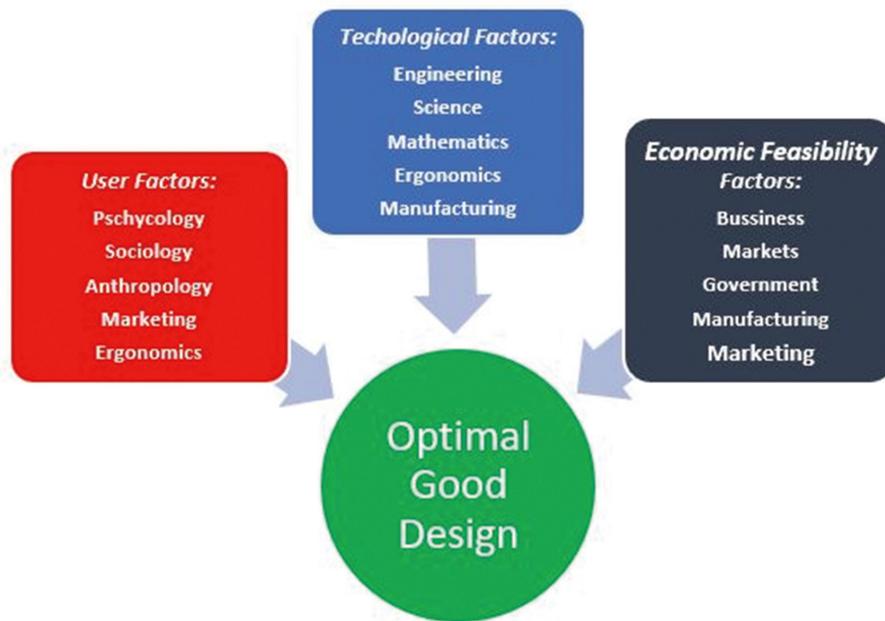For an instance, Georgios Kazakis, Ioannis Kanello-

Figure 1. An Optimal Good Design Concept Factors

poulos, Stefanos Sotiropoulos and Nikos D. Largaros [7], incorporate smart and automated structural computational tools that utilize computational techniques related to topology optimization in civil structural design very logically. The structural topology optimization problem is solved using material distribution methods, L. Spunt [8] for achieving the optimum design layout of a structural system made from linearly elastic isotropic material. For this purpose, a compliance criterion is minimized by adjustment of the material distribution volume into a design domain. The distribution of the material volume in domain is controlled by the density values distributed over the domain. More specifically, it is controlled by design parameters that are represented by the densities assigned to the FE (Finite Element Method) discretization of domain. The FE simulation tool, while under iterative mode, calculates the design variables as the material concentration density is changed. The design variables are limited to strength and displacement outputs that are generated under the applied fixed input loads set at the initiation of the optimization runs. The optimization iteration cycle for an optimally good design is shown in Figure 2 following. Geometry of a product or a system is simulated and material mechanical property definitions are set. Constraint sets are established to define the displacement and strength limits. Once the design analysis is initiated a limit comparison is made against the constraint sets. Material concentration densities are adjusted and once again limit comparisons against the constraint sets are made. Determination of "good design" based on the criterion are made. Iteration process is started until an "optimal" good design is achieved.
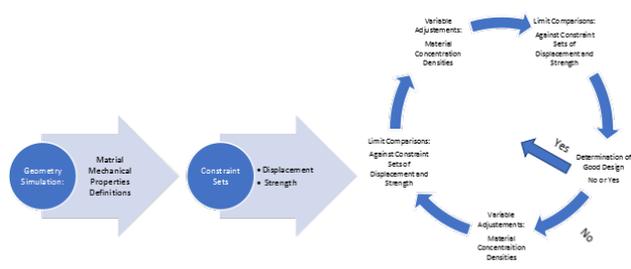

Figure 2. Automatic Optimization Iterations for an Optimal Good Design

The aforementioned research work was mentioned to explore the numerical method aspects of optimal design in a design process via engineering sciences. It is next necessary to explore the user factors in optimal design. It was stated earlier that psychology and sociology are the user factor criterion for design. This is where ergonomics and marketability of the design have to be considered in an optimal design. A design "must" be ergonomically ideal for the user and the design engineer must give maximum considerations for user comfort and safety. The engineering mindset that considers the comfort and safety of the end user always has the best features embedded in the system design or in the component design by definition. Designing for safety by definition has the safety factors embedded in design and any malfunctions are minimized as the design safety is accomplished. In some instances, fail-safe conditions are also a component of the safe design, where as possible failure of the subcomponents of the system does not necessarily indicate a catastrophic failure but rather a controlled failure. These factors in combination with other factors are normally driven by the governmental factors/requirements.

Leading to the final stages of the "good design", economic factors that are based on market, business and government criterion are the most important factors in a good optimal design. For instance, in the telecommunication industry an optimal design considers all applicable IEEE standards which constitute the business standards of the best design process practice. In civil structure designs, in mechanical and aerospace designs ASTM standards for material characterization are standards of the best design process practice for use of material properties. As another example, in automotive engineering SAE standards are criterion that are used for best business standards and practices. Government regulations as set by organizations such as National Highway Traffic Safety Administration (NHTSA), Federal Aviation Administration (FAA) and Individual State and Municipality Building Code Administrations are some of the good examples for a good optimal design requirements.

2. Benefits of Design Optimization for an Optimal Good Design

Historically, design variations done by engineers were limited to shape optimization as a whole with one or two cumbersome iterations only. Automatic design optimizations via computational simulation methods introduced topological optimizations that varied design topology and saved material costs and weight. The concept of varying material density concentration on a system or a part component design as a specific example was unknown and unfeasible in the past. For instance, an airplane part could only be designed with the outside dimensional boundaries varying in an iteration or two. The concept of material concentration density adjustment was unfeasible and far out to reach concept in early days. Computational tools such as FEA (Finite Element Analysis) provided the

means for such automatic optimization schemes because design variables now can be parametrized and change in them was feasible and not time consuming thus making such optimization efforts possible and reachable. The general application of FEA for optimal design is illustrated in Figure 3 following.
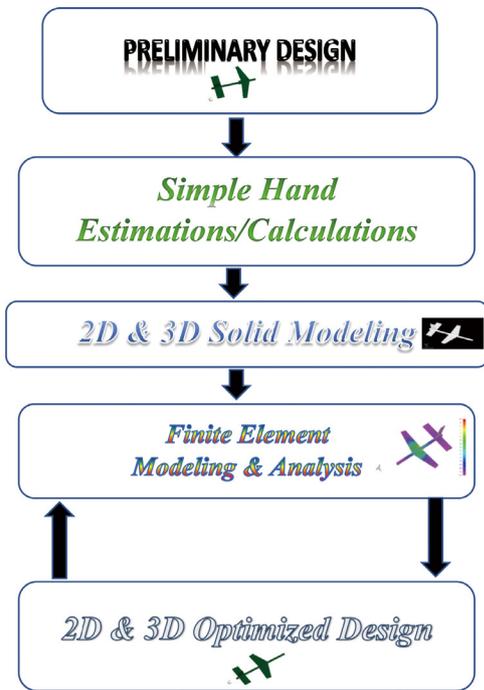

Figure 3. FEA Application for Design Iterations

3. Mathematical Optimization Theory Behind (Numerical Methods)

The best means of defining optimization theory in design is by defining the mathematical concept of the optimization. Mathematical Optimization as defined by J. Snyman [9], is a formal process of formulation and the solution of a constrained problem of the general form.

$$\text{Minimize } f(x), x = [x_1, x_2, .., x_n]^T \in R^n \tag{1}$$

w.r.t: x
Subject to constraints:

$$g_j(x) \leq 0, j = 1, 2, \ldots, m \tag{2}$$

$$h_j(x) = 0, j = 1, 2, \ldots, r \tag{3}$$

Where $f(x)$, $g_j(x)$ and $h_j(x)$ are scalar functions of the real *column vector x*. The continuous components x_i of $x = [x_1, x_2, \ldots, x_n]^T$ are called the (*design*) *variables*, $f(x)$ is the *objective function*, $g_j(x)$ denotes the respective *inequality constraint functions* and $h_j(x)$ the *equality constraint functions*.

The optimum vector x that solves problems (1) and (2) is denoted by *x** with corresponding optimum function value *f(x*)*. Mathematically if no constraint sets are specified, the problem is called an *unconstrained* minimization problem.

The iterative means of reaching the solution by minimization optimum function are done by numerical and computational methods; as an example of such cycle was provided with Figure 2 illustrations before.

In general optimization can take effect by means of shape, size or topology, Il Yong Kim, Byung Man Kwak [16], Raino A.E. Makinen, Jacques Periaux and Jari Toivanen [17], C. Onwabiko [18]. There are two main methods for achieving an optimization. One method is the gradient-based method and the other method is Heuristic method. For gradient based method minimization is done based on a function that could hold constraints or be unconstrained. The method tests for convergence of the solution function and if no optimal design is achieved a search in the domain space is done by updating the design variables until a desired optimal design solution is reached, C Onwabiko [18].

Heuristic methods are computational procedures that find an optimal solution by iterative means that improve on sample solution with respect to a given measure of quality. It is randomization of the solution with implementation of genetic algorithms, simulated annealing or tabu search method, Wang, F.S., Chen, L.H. [19].

4. Optimization Design Theory Applicability

The applicability of automatic optimization design theory here in this presentation is somewhat constrained to a specific example of structural optimization. However, the mathematical model can be applicable to any engineering design concept optimization. Likewise, the same theory can be applied to a heat exchanger design concept whereas optimal pipe sizing and pipe count are the objectives of a good design, Bahri Sahin, Yasin Ust, Ismail Teke and Hasan H. Erdem [10]. In this type of research the objective function is defined as the actual heat transfer rate per unit total cost considering lost energy and investment costs. The optimal performance and design parameters which maximize the objective function are investigated with the effects of varying technical and economical parameters. Figure 4 following attempts to illustrate a quasi-realistic typical design optimization effort. As the number of iterations go up the cost has to come down and an optimal design has to be reached all at the same time. This representation is fictional for illustrative purposes and only represents a first pass iter-

ation segment cut of the optimization theory objective. In reality, this iteration could be chaotic or non-chaotic depending on the sensitivity required for convergence.
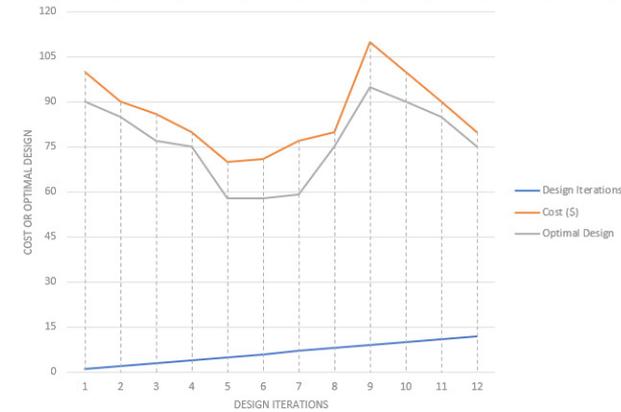

Figure 4. Design Optimization Theory Objective

For illustration purposes let's assume a simple part as shown by the Figure 5 following. This is a part model represented in a CAD model with the illustrated dimensions. One can discretize the model with finite element representation of the model as shown by Figure 6 following. An applied load of 100 pounds is applied to the tip of the part and the part is being held fixed on the other end as shown in Figure 6. The Figure 7 illustrates the first run FEM model with the highest stress level to be around 17ksi. There are many regions within the part design that have very small magnitude of stress concentration level. After the trim and geometric optimization of the external boundary of the part, the second run of FEM analysis is performed. At the second run after optimization based on the stress concentration locations shown the highest stress levels are around 64ksi with about 3% weight reduction. The third and final run the highest stress level is around 79ksi with about 30% weight reduction with the part structural region. The total processing time for this typical part optimization was about 60 minutes to perform a 30% weight reduction.
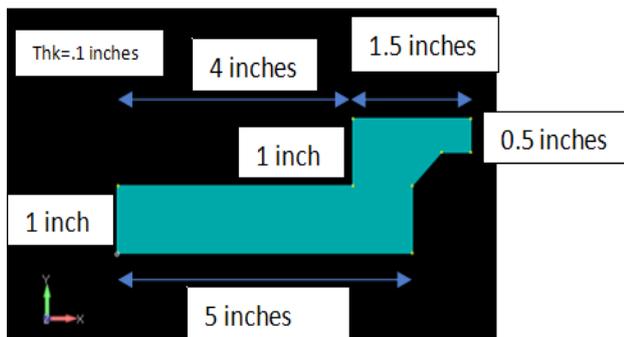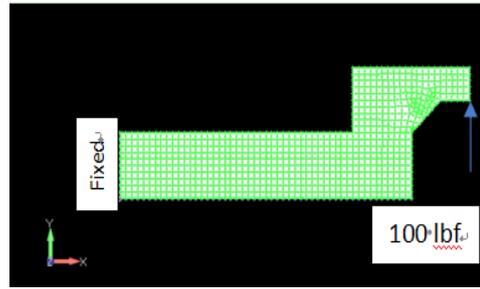

Figure 5. CAD Model of a Part

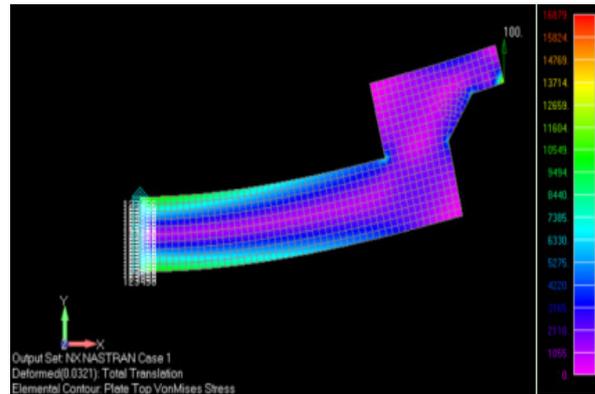**Figure 6.** Discretized FEM Model of the Part with BC's

Figure 7. First run of the FEM with the 100 lbs load at the tip
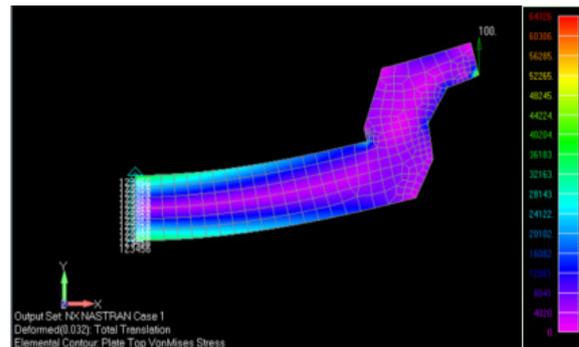

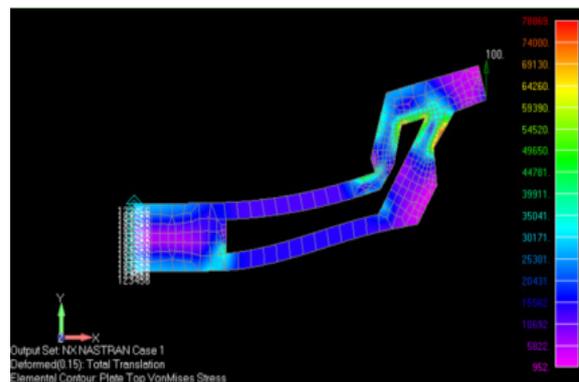**Figure 8.** First Run Optimization of the FEM Model (3% weight reduction)

Figure 9. Second Run Optimization of the FEM Model (30% weight reduction)

In a manufacturing environment, technical and economical parameters are also a design factor for an optimal good design; the same optimization theory is applicable as well too. In a study done by Cezarina, Afteni and Gabriel Frumuşanu [11], a systematic analysis of already published works on formulating and solving optimization problems concerning manufacturing process are presented. The review work done by Cezarina, Afteni and Gabreil Frumuşanu [11] indicate optimization was performed on two levels, namely: planning and scheduling of manufacturing process. Mono-criterion or multi-criteria type of optimization with objective functions set as the energy consumption, the manufacturing costs, the productivity and the manufactured surface roughness were considered. Interestingly, Genetic Algorithms (GA), Particle Swarm Optimization (PSO) technique and Artificial Neural Networks (ANN) are among the methods reviewed for optimization (GA utilization is considered another advanced mathematical theory of optimization).

Furthermore, an advanced improved optimization theory applicable to aircraft sizing problem has been examined by Li, Wei; Xiao, Mi and Gao, Liang [12]. An optimization method is introduced by the authors where three subsystems, aerodynamics, weight and performance are considered. The objective of this optimization is to minimize the total weight of aircraft subject to constraints on the aircraft range and stall speed of the aircraft. This work is indicative that the robustness of the objective and constraints functions simultaneously should be considered for construction of a robustness discrepancy that guides the optimization sampling problem. At first initial feasible solutions are used to build this robustness discrepancy. In detail a set of uncertain candidates that have smaller robustness discrepancy values are selected that meet the robustness requirements. Then a method known as MPS method is used as a global optimizer to achieve the optimal solution. Finally, a sampling method known as ICPM is utilized to address the optimization problem with uncertainties where it is carried out by 9 discrete mathematical steps that are explained in this research work by Li, Wei et al. These types of multidisciplinary robust design optimization methods gain more and more applications in research, Wang X, Wang R, Chen X and Geng X [13] and Zaman K, Mahadevan S [14], where complex design problems with large uncertainties exists.

5. Concepts of Optimal Good Design for the Future

With the new industrial revolution of digitization tak-

ing form recently, the good design theory is achieving new levels of complexity and outcome [22]. Not only a good design would be optimized locally at the engineer's simulation level but also it will be optimized and processed via multiple end users and functional inputs. A typical design can have inputs from manufacturing and fabrication facilities, installation and modification sites, marketing inputs, industrial design branch and finally but not least the end user-customer [23].

Decentralizing the decision-making process and information transparency are the main factors of digitization era in design concepts that drive the optimal design in the future. The power of advanced next generation data networks along side with digitization efforts and rendering provide these optimal designs in matter of hours if not minutes depending on the complexity of the problem at hand. Ease of access to design data and design data always being accessible is another advantage of digitization being incorporated into the design process. This concept minimizes the wait time to review and update any design as it allows simultaneous access of design by different people who are involved.

Knowing all that, to progress in this 4th industrial revolution era, understanding classical design optimization theory and application of it, is a must to know venture. Design engineers should not neglect the need to fully understand the classical design optimization theories in order to move forward or at least prove not to be inefficient in the future as the digitization revolution sets in place.
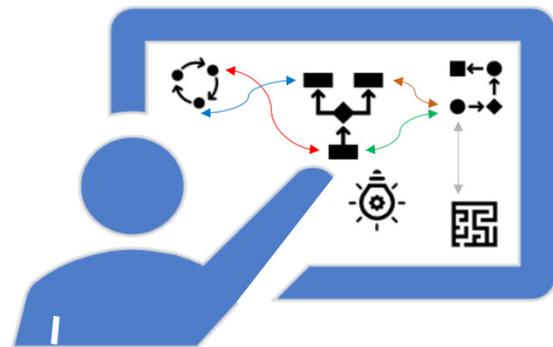

Figure 10. Concepts of Optimal Design for the Future

6. Multidisciplinary Nature of Design

Unlike the early eras of technology development in the world whereas a design was only carried out by one "design engineer" who had basic knowledge of every related field for the design, in this age the designs are 99%

multidisciplinary efforts. In fact, if different subject matter expert engineers are not involved in the design process, the design is destined to be an average design if not a substandard design for certain. The need for reduction of cost by utilization of advanced materials, materials processes and fabrication techniques requires multidisciplinary expertise for a "good design". The technology has advanced so much and so rapidly that for sure one engineer is not capable of having the full knowledge to carry a "good design" solely by relying on himself or herself alone without other engineers in other disciplines.

7. Discussion

This paper tries to elaborate that most of the engineering and scientific design problems can be optimized for a good design based on many new optimization techniques discussed here. The work presented in this paper implies that there are many factors associated with a good design and further there are a vast variety of optimization techniques that exist in achieving the good design. The user factors, technological and financial feasibility factors that are known, have to be considered in any design problem. Each factor has to be given a real value and each value has to be scaled in the order of the importance. Based on these factors, the parameters for the optimization have to be set and each of the factors has to be translated into design variables and state variables in a scientific manner. The survey of design optimization applications that are sampled in this paper are indicative that there are many numerical and scientific methods in achieving an optimal good design. Thus, depending on the complexity and the degree of uncertainties associated with the design, the optimization can be formulated literally in math models that materialize the robust optimization goals that take away the randomness. It needs to be added that a solid background in mathematical and numerical modeling is a must for achieving a good engineering design [20, 21].

8. Conclusions

The concepts of the good design and optimal good design theory were examined here in this paper. Factors associated with a good design concept; Technological factors, user factors and economic factors were defined and established as tools for a good design concept. Design thinking and system engineering design thinking were elaborated. Design optimization theory with several practical applications in civil structures design, heat exchanger design and manufacturing operation design was discussed in details. The general mathematical theory of optimization was intro-

duced and its application to any design process was emphasized. Future trends of design optimization for a good design in the new era of digitization revolution was discussed and the design engineer's need to familiarize oneself with the classical design optimization theory was emphasized.

References

[1] Accreditation Board of Engineering and Technology (2020), Criteria for Accrediting Engineering Programs-2019-2020, http://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/#GC5

[2] Ertas, A. & Jones, J. (1996), The Engineering Design Process. 2nd ed. John Wiley & Sons, Inc., New York, N.Y.

[3] Altringer, B., & Habbal, F. (2015), Embedding Design Thinking in a Multidisciplinary Engineering Curriculum. In National Collegiate Inventors and Innovators Alliance (pp. 1–13). Hadley, Massachusetts. Retrieved from http://search.proquest.com/docview/1749280842?accountid=14701\nhttp://sfx.scholarsportal.info/ottawa?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:journal&genre=article&sid=ProQ:ProQ:entrepreneurship&atitle=EMBEDDING+DESIGN+THINKING+IN+A+-MULTIDISC--

[4] Melissa T. Greene, Richard Gonzales, Panos Y. Papalambros and Anna-Maria McGowan (2017), Design Thinking vs. System Thinking for Engineering Designs: What's the difference, 21st International Conference on Engineering Design, Vancouver, Canada.

[5] Forrester, Jay. (1994), System Dynamics, Systems Thinking and Soft OR, System Dynamics Review, Vol. 10(2) pp. 1-14.
DOI: https://doi.org/10.1002/sdr.4260100211

[6] Ludwig Von Bertalanffy (1940), An Outline of General Systems Theory, British Journal for the Philosophy of Science, Vol. 1 (2) pp. 134-165.
DOI: https://doi.org/10.1177/053901846700600610

[7] Georgios Kazakis, Ioannis Kanellopoulos, Stefanos Sotiropoulos, Nikos D. Lagaros (2017), Topology optimization aided structural design: Interpretation, computational aspects and 3D printing. Heliyon, Vol. 3 e00431.
DOI: https://doi.org/10.1016/j.heliyon.2017.e00431

[8] L. Spunt (1971), Optimum Structural Design, Prentice-Hall, Englewood Cliffs, New Jersey, USA.

[9] Jan N. Snyman (2005), Practical Mathematical Optimization, Springer Science+Business Media, Inc.

[10] Bahri Sahin, Yasin Ust, Ismail Teke and Hasan Huseyin Erdem (2010), Performance analysis and opti-

mization of heat exchangers: a new thermoeconomic approach, Journal of Applied Thermal Engineering, Vol. 30, Issues 2–3, pp. 104-109.
DOI: https://doi.org/10.1016/j.applthermaleng.2009.07.004

[11] Cezarina, Afteni and Frumuşanu, Gabriel (2017) A Review on Optimization of Manufacturing Process Performance, International Journal of Modeling and Optimization, Vol. 7(3): 139-144.
DOI: https://doi.org/10.7763/IJMO.2017.V7.573

[12] Wei Li, Mi Xiao and Liang Gao (2019), Improved Collaboration Pursing Method for Multidisciplinary Robust Design Optimization, Structural and Multidisciplinary Optimization Journal, pp. 1949-1968.
DOI: https://doi.org/10.1007/s00158-018-2165-2

[13] Wang X, Wang R, Chen X and Geng X (2018), An efficient single loop strategy for reliability-based multidisciplinary design optimization under non-probabilistic set theory, Aerospace Science Technology, Vol. 73: 148-163. https://doi.org/10.1016/j.ast.2017.11.046.

[14] Zaman K and Mahadevan S (2013), Robustness-based design optimization of multidisciplinary system under epistemic uncertainty, American Institute of Aeronautics and Astronautics Journal Vol. 51(5): 1021-1031.
DOI: https://doi.org/10.2514/1.J051372

[15] Martin O. Bendose and N Kikuchi (1988), Generating Optimal topologies in structural design using a homogenization method, Journal of Computational Method Appl Mech Engr, Vol. 71: 197-224.
DOI: http://dx.doi.org/10.1016/0045-7825(88)90086-2

[16] Il Yong Kim and Byung Man Kwak (2002), Design Space Optimization using a Numerical Design Continuation Method, International Journal for Numerical Methods in Engineering, Vol. 53: 1979-2002.
DOI: http://dx.doi.org/10.1002/nme.369

[17] Raino A.E. Makinen, Jacques Periaux and Jari Toivanen (1999), Multidisciplinary Shape Optimization in Aerodynamics, electromagnetics using genetic algorithms, Int Journal for Numerical Methods in Fluid, Vol. 30: 149-159.
DOI: https://doi.org/10.1002/(SICI)1097-0363(19990530)30:2<149::AID-FLD829>3.0.CO;2-B

[18] C. Onwabiko (2000), Introduction to Engineering Design Optimization, Prentice Hall, U.S.A.

[19] Wang, F.S., Chen, L.H. (2013), Heuristic Optimization, Encyclopedia of Biology Systems, Springer, New York NY.

[20] Pahl, G., Beitz, W., Feldhusen, J. and Grote, K-H. (2007), Engineering Design: A Systematic Approach, Springer, New York NY.

[21] Pugh, S. (1991), Total Design: Integration Methods for Successful Product Engineering, University of Michigan, Ann Arbor, Michigan.

[22] Company Blog, (2019), How digitalisation is changing the world of engineering, Item Industrietechnik GmbH, Germany.

[23] Zhou, J., (2013), Digitalization and intelligentization of manufacturing industry. Adv. Manuf. 1, 1-7.