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GENERATIVE DESIGN: ADVANCED DESIGN OPTIMIZATION PROCESSES FOR AERONAUTICAL APPLICATIONS

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Abstract

Current researches on aircraft design aim to reduce airplanes and components weights, optimizing aircraft performances and contributing to the challenge of reducing fuel consumption and operational costs.
In this perspective novel materials and technologies are developed, but also advances in design methods and tools. Generative Design is a novel approach to automatically optimize component design. The design process has to be designed itself to achieve the optimal solution, in relation to design parameters, requirements and limits.
Which peculiar features justify considering this technique to be a substantial step forward with respect to classical MDO? Could Generative Design be only an important, but not particularly differentiated approach for the design of (aerospace) structures and possibly systems of a higher level? For example, when the design goal is to find the best configuration of a structure, does generative design lead to the discovery of new concepts, or types of structures, or it is a particular application of genetic algorithms to topological optimization? This paper aims to contribute to give an answer to the previous questions. Specifically, the generative design approach is expected to be able to select between basic concepts and use these as the basic instructions and ingredients of a recipe for the design of a new system.
By these considerations, in this paper, we revised the improvements brought by Generative Design principles within the traditional design procedure in aeronautics, considering Additive Manufacturing technology.

1 Introduction

More flights, more potential passengers, fewer emissions and shorter travel time will mark future and challenges of aviation. According to such a vision, aircraft design is a balance between costs, environmental aspects, regulations, airliners' requirements and aircraft performances. Design methods and tools have to develop accordingly. Innovative technologies and materials will support designers in searching new solutions and processes. In this way, innovation in design methods changes common paradigms: the cross fertilization coming from incorporating concepts derived from many disciplines and their integration with advanced manufacturing systems and materials may improve design results.
Inspired by the natural design processes and patterns of nature, Generative Design is a design method for capturing the designer's intent, generating new solutions. Characterized by *data-driven collaborative cloud-based technology*, it relies upon a highly automated activity. A set of parameters and rules (commands to the designer) is considered as the DNA of the design process; rules and parameters are considered as the "genes". They are combined by evolutionary algorithms or even "brute force" computations. The introduction of such procedures into the design process allows the development of novel design solutions by modifying the rules that define a final design, difficult or impossible to achieve via other methods. Grammar-based techniques exploit the principle of database amplification,

the identification of rules, generating complex forms and patterns from simple specifications.
Generative design principles received a particular attention in architecture; some good definitions coming from that field are reported here [1]:

- "*Generative design is not about designing the building – It's about designing the system that builds a building.*" – Lars Hesselgren;
- "*Generative Design Processes is about the modelling of initial conditions of an object (its "genetics") instead of modelling the final form.*" – Paola Fontana;
- "*Generative design systems are aimed at creating new design processes that produce spatially novel yet efficient and buildable designs through exploitation of current computing and manufacturing capabilities*" – Kristina Shea.

1.1 Generative Design within the Design for Additive Manufacturing approach

Nowadays it is generally accepted that in Aerospace and Industrial applications, we can achieve the main advantages from the introduction of advanced design procedures, if we combine them with Additive Manufacturing (AM) processes and techniques.
Therefore, we have to take into account also the coupling of evolutionary algorithms with innovative manufacturing processes, like Additive Manufacturing, and new materials. This combination introduces more degrees of freedom in the final design concept: for example, the mixing of materials with different properties allows having different properties distributed in different zones of the same part, leading to multi-functional concepts.
The opportunities offered by AM are not restricted to multi-functional concepts. Consider that, over the last years, AM's adoption has increased across industries, with the aerospace industry contributing about 10.2% of AM's global revenues in 2012. AM provides the flexibility to create complex part geometries that are difficult to build using traditional manufacturing, such as internal cavities or lattice structures that help reduce parts' weight without compromising their mechanical performance [2]. Furthermore, AM's impact on economies of scale and scope make it a natural fit for Aerospace, which is largely geared toward customized production. A synthetic overview of current and potential applications is reported in Figure 1.

	Current applications	Potential applications
Commercial aerospace and defense	• Concept modeling and prototyping • Printing low-volume complex aerospace parts • Printing replacements parts	• Embedding additively manufactured electronics directly on parts • Printing aircraft wings • Printing complex engine parts • Printing repair parts on the battlefield
Space	• Printing specialized parts for space exploration • Printing structures using lightweight, high-strength materials • Printing parts with minimal waste	• Printing on-demand parts/spares in space • Printing large structures directly in space, thus circumventing launch vehicles' size limitations

Sources: Deloitte analysis; CSC, *3D printing and the future of manufacturing*, 2012.

Fig.1 – Current and future applications of AM in Aerospace industries

The new system, once manufactured thanks to AM, should satisfy to the functional requirements in an innovative and more efficient way, targeting also a simpler design and a substantial cost reduction. Novel structural materials and advanced AM techniques make these technologies ready to be introduced within the generative design process also for safety critical context, such as the aeronautical.
Even if the advantages from the introduction of the couple Generative Design and Additive Manufacturing has been widely considered, only some case studies have been provided in architecture, styling and biomedical applications, but has not be explored enough in aerospace.

2 Generative Design approach in product development and aeronautical industry

Typical Aircraft design practices consider the design process spread into three main phases: the conceptual design, the preliminary design and the detailed design. The design solution is proposed throughout the typical diverging – converging process, in relation to design requirements and limits. Multidisciplinary optimization processes are currently being developed to support designer in assessing the optimal solution, in relation to all design features and parameters.
Generative Design is a novel form-finding process that takes into account structural performances, material properties and

ergonomic demand, throughout an automatic iterative holistic approach for component topology optimization [3]. The design approach is grammar based, and the design activity itself has to be designed, on the basis of evolutionary algorithms in order to meet the optimal scoring for an objective fitness function [4]. Evolutionary design approaches limits to performing the numerical optimization on the set of design parameters [5].

On the other side, Topology Optimization intends to find an optimal structural configuration within a given design domain for specified objectives, constraints, loads and boundary conditions. In general, it relates to size or shape optimization issues [6], , with particular regards to component weight reduction: optimized configurations are defined re-distributing the material in the design domains with the prescribed loads and boundary conditions.

Generative Design includes both Evolutionary Design and Topological Optimization, but it is not limited to that.

After years of research and development, some specialized Generative Design tools are becoming part of CAD/CAE platforms and are entering the market [8].

A company developed software to be integrated with industry-leading Building Information Model (BIM) and CAD platforms. This software includes *"two classes of tools: the first class connects existing tools together to allow seamless execution of complex workflows, and the second class captures design intent."*

Within the typical diverging – converging design process, it is introduced the generative design domain for concept selection: the trade-off between component performances, weights and costs is simplified and the multidisciplinary optimization approach is improved, see Fig.2.

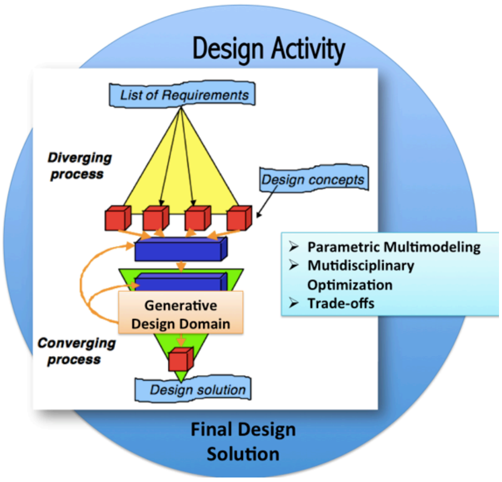

Fig.2 – Scheme of Generative Design role in the design activity

Even if in simpler case studies, the generative representation derived from evolutionary design, where the Evolutionary Design System is able to explore the space of design topologies, advanced Generative Design System and Tools should include some key aspects both in the design features and in the representation of the solutions: modularity, regularity and hierarchy. Modules are at the base of the design representation and they are hierarchically formed and could be combined or reused to define the final topology optimization [9].

From a computer programming language point of view, rule-based design-construction programs define the design-programming tool. Subprocedure-like elements are at the basis of the modularity feature; iterative loops and sub-procedures enable the regularity role and a nest-base approach defines the hierarchy, to link all the sub-procedures and loops, within an assembly procedure.

The final achieved design is optimized in accordance of the proposed requirements and limits and consists in a "family of designs" according to different parameters that could be used as input to the defined rules or changing the objective fitness function (Figure 3) [9].

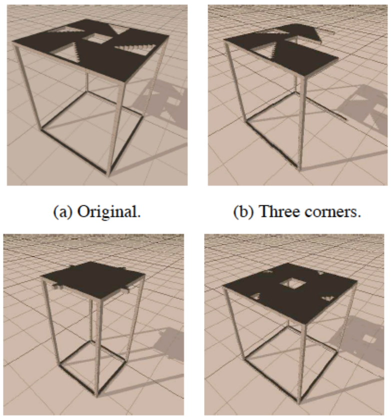

Fig.3 Generative design examples: mutations of the results according to encoded design changes [9]

In [10], authors consider the digital design process as the composition of two main activities: physics-based processes, to perform the simulation of complex natural phenomenon, followed by a progressive formation and mutation to allow the creation and dynamic evolution of the simulation components.

Thanks to its ability to generate novel, unconventional and complex structures (Fig. 4), developers and supporters consider Generative Design one of the most promising methods to be explored for evolving new designs, and suited for aerospace applications, even if it is not enough explored.

Fig.4 GD outcome using Additive Manufacturing performances [8] in the automotive field: design of a load-bearing engine block

3 Methods and tools for Generative Design

Driving the design process, the human designer has a central role to create and define the most suitable design solution. In this framework novel CAD tools have been developed to support designer in his creative role, and they have to meet the following requirements:

- The signer dependency is less demanding and less disruption to work processes;
- Allowing designers to navigate through the whole design space;
- Supporting chaotic and unstructured work processes;
- Structured as an auxiliary tool;
- Support and enable the emergence of the designer in order to stimulate creativity;
- The content of the detailed design phase of the design to be effective.

CAD tools enabled for Generative Design practices do not have a pre-structured workflow; furthermore, the design development process is couple with the generation of new knowledge about the design problem at each step of the iterative procedure.

Recently several "generative design software tools" have been released, provided either as part of CAE (Computer Aided Engineering) Suite such as Autodesk and Dassault Systèmes products or as stand alone applications (namely Genoform and nTopology Element) with different levels of interoperability with the existing CAD software.

Those tools that are part of CAE Suites exploit the FEM tools to provide the user with a support tool in designing full stressed components that maximize the efficiency of the structural function. The design space is drawn by the user as the envelope the component should fit in. Loads and constraints are applied in a similar manner as in the FEM tools, and the target optimization function is selected (e.g. minimum weight, maximum stiffness). As a result of the optimization algorithm applied a single solution is provided to the user by means of a rough model that should be then manually refined in order to obtain an acceptable solution.

Those tools are powerful from a structural engineering point of view, however they are not fully capturing the creative intent of the designer.

On the other hand, the generative design stand alone applications (those that are not part of a CAE Suite) are providing the designer with a set of alternative product configurations that can be evaluated by the designer against aesthetical, structural or functional criteria using the appropriate tool for each relevant criterion. Genoforming parametric CAD systems are based on CAD parametric models, they are plugin applications that work acting on the parameters of CAD programs by means of genetic algorithm. Specific features allow the user to control the level of creative exploration by a slider bar (Genoform).

4 Generative Design principles in component development: case studies

Some case studies are presented in literature to assess the design improvements from the introduction of Generative Design principles within the typical product development procedure. Generally speaking, the design optimization activity has the main objective to provide a significant weight saving; furthermore, nowadays, advanced components are designed to be directly manufactured by an additive technique.
Generative design process starts with a designer defining a design area, connection points linked by parameters. An example can be seen in Figure 5, where these parameters are defined for a motorcycle swing arm design [11]. Optimization is based on desired materials, manufacturing technologies, temperature tolerance, cost, and strength of the part and its ability to withstand specified forces.

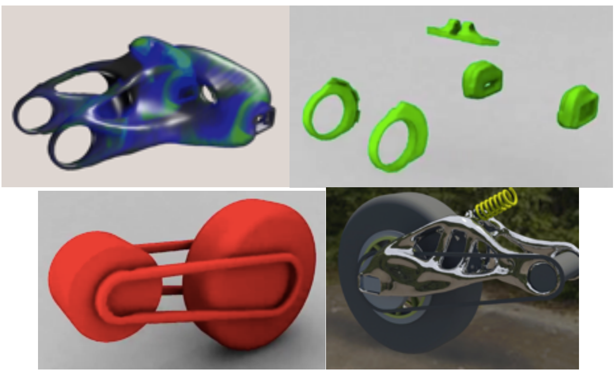

Fig.5 Generative design of a motorcycle swing arm: bounding space (on the top left), connections (on the top right), limits (on the bottom left) and design output (on the bottom left) [11]

Innovative tools for Generative Design support the designer to fit all defined constraints, and to meet requirements. An efficiently high automation level support all design tasks, including aesthetics features and the definition of innovative and effective models to explore, reducing the design time and improving the design results.
Within Autodesk Research framework, Project Dreamcatcher allow designer to iterative define some most suitable solutions, testing the strength and removing unnecessary material at each design step [11]. The designer role is also to choose the best one and to modify it according to some specific additional requirements.
Airbus and Autodesk have developed one of the most effective examples of Generative Design in aeronautics [12]. Cabin partitions are designed to be manufactured by a 3D additive manufacturing process. Custom algorithms have been developed to generate unconventional structures to mimics cellular shapes and bone growth. Stronger and lighter micro-lattice new bionic partition structures are designed. Each model is 45 per cent (30 kg) lighter than current designs. When applied to A320 cabin it results in a reduction of 465,000 metric tons of C02 emissions per year. Laser Powder Bed Additive Layer Manufacturing (ALM) processes is the technology used to manufacture the novel bionic partitions. Scalmalloy® is the high-performance aluminium powder used for the 3D printing process, thanks to its high strength and tough properties, combined with low weight of aluminium alloys.

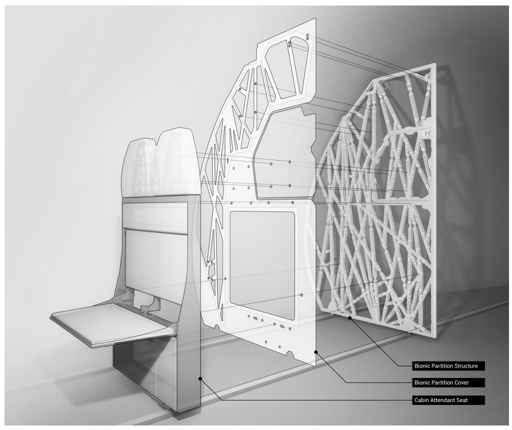

Fig.6 Novel bionic partition for Airbus A 320 cabin interiors [12]: the goals are met by coupling generative design with an additive manufacturing technique and the introduction of novel materials

The Generative Design approach considers a defined base model; a macro and micro geometry optimization process are iteratively carried out. At a macro scale, the algorithm sketch lines to network many reference points, while at a micro scale a logic similar to bone growth is applied to support the highest strength areas of the structure (Figure 7).

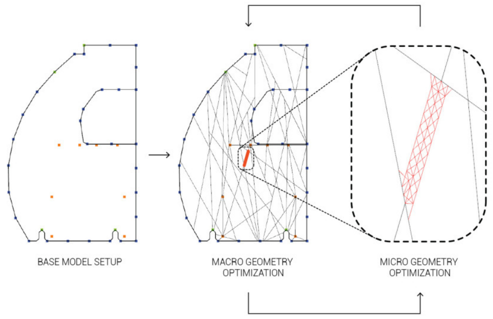

Fig.7 Design approach of the algorithm developed within Autodesk to meet Airbus cabin interiors by Generative Design [12]

Conclusions

Generative Design is a novel procedure to support designer in widely explore the design space. It is not only a topology optimization, neither an evolutionary algorithm, but it combines several optimization modules to topology definition within a CAD environment, according to design requirements, limits and the bounding space. The output is not only the most suitable solution, while it is a family of different results that the designer could properly select and modify. The solution space is generally developed considering freeform shapes: it would not be possible to reach a better solution by means of a traditional design approach. Furthermore, the selected shape is designed to be manufacture by an Additive Manufacturing process.

Even if some case studies and some tools have been developed, the potentials brought by Generative Design principles are not yet explored enough. Some examples have been considered in small component design, but only few cases and tests are proposed in aeronautics. Low weight and structure's strength used to be the main objectives of aircraft component design. In this framework the development of robust design procedure that include Generative Design principles would bring great improvements both in components' feature and design results and in design time reduction as well as aircraft operational costs, since a huge reduction of structures' weight is foreseen.

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