INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.181

Generative Product Design Processes: Humans and Machines Towards a Symbiotic Balance

M. Tufarelli ✉ and E. Cianfanelli

University of Florence, Italy
✉ margherita.tufarelli@unifi.it

Abstract

Design processes managed by algorithms provide solutions and improvements in terms of efficiency, performance, choice of materials, and cost optimization. It is a whole new approach to industrial design in which artificial intelligence participates directly in the design processes. The paper aims to investigate the way we design through algorithms, and consequent changes in thoughts, approaches, and generation of ideas that are rising determining new ways of defining things and their relations.

Keywords: *generative design, product design, advanced manufacturing, design process, industrial design*

1. Transformative times

The theme of transformation has forcefully entered the academic, productive, and social debate in multiple contexts, thanks to a collective awareness that returns the need to explore the emerging paradigms of change. With the disruptive Digital Transformation (DX), it is evident that technologies extend and expand most of the human actions to the digital environment, profoundly changing them in objectives, methods, and tools. Scholars and practitioners define this as a phenomenon that affects operational, organizational, and managerial aspects, imposing changes in the meaning of many human activities, including design and production processes.

The paper aims to address this intense path that is returning profound technical-scientific and economic-productive changes that digital tools can conduct, involving both the input (design-management-control methods), as well as the output (product performances and meanings). The former is facing the integration of physical processes with computational ones; the latter manifests itself in the transition phenomenon that invests everyday products: from mechanical or electrical, they become complex systems that combine hardware, sensors, data storage, microprocessors, software and connectivity.

In these terms, it is evident that with Digital Transformation (DX), technologies lay the foundations of a new world, having a transversal impact on the products of the future (McKnight, 2017), on the ways of *doing things* and *living places*, proposing new subject-object relationship of radically different complexity.

In the last decade, rapid technological advances returned new supporting tools in the design-production realm such as Big Data, Industrial Internet of things (IIoT), Additive Manufacturing, Artificial Intelligence algorithms, cloud computing, and generative design tools, transforming, translating, distorting, and modifying the meaning of elements they are supposed to carry. Hence, Digital technologies can change the way we innovate and deliver value (Magistretti et al. 2019) by

introducing complex dynamics in which the range of material, immaterial and digital manifestations extend fluidly across different domains, which are mobile and combinable.
It is a disruptive transformation that affects all aspects of human thinking and production. With Manovich (2001), “we are facing the shift of all cultures to computer-mediated forms of production, distribution, and communication". Digitization, therefore, has a deep impact on design culture as it addresses production, organization, and transmission, returning a scenario more relevant than ever for design which is challenged by a profoundly transformed design process (Meyer et al., 2021), operating in an increasingly fluid environment with blurred boundaries between physical, digital, and biological spheres.
Yet nowadays it seems that technology is dictating the rules of change: the extent of technological advancement will entail a complex underlying cultural maneuver, since industrial products, both in appearance and in performance, will be placed in contexts in which technology will offer new social, environmental and cultural values. Technology operates directly on the way we know the world, offering new cognitive paradigms from which new internal approaches emerge to the design culture, which is now called to achieve a symbiotic balance between design intelligence and artificial intelligence.
In this framework, computational environments and design processes managed by algorithms rise, intending to provide solutions and improvements in terms of efficiency, performance, choice of materials, and cost optimization. It is a whole new approach to industrial design which provides for the delegation of some optimization operations to the algorithms, which offer real-time solutions and great acceleration in all phases of the project.
The new tools are reshaping the design approaches and industrial processes as well, influencing the theory and practice of design. Looking at the product design and development scenario, AI provides agile and real-time integrated environments, in which design becomes more digital than ever: the computational and generative design application confronts a data-based paradigm in manufacturing environments, which directly affects product design and development processes.
Hence, the adoption of generative design technologies within the design process raises a series of critical questions for the future that the contribution aims to discuss. The field offers significant space for reflection in this sense, as it places the design processes within software environments, in charge of elaborating the design inputs, directly entrusted to the algorithms. Thus artificial intelligence supports (or frees?) Human creativity in the conception of artifacts, bringing out new spaces for post-algorithm design and significant changes in the design process as well.

2. Digital takes command

The ever-closer relationship between design and computer science stimulates numerous reflections nurtured by an increase in complexity that has progressively invested in the design field, imposing the demand for specific knowledge that goes beyond the conventional boundaries in which the designer operates. Contemporary complexity, in fact, increasingly needs collaboration between different kinds of knowledge and skills in order to be faced and dissipated: the boundaries between professions become blurred and permeable, offering great opportunities, but also new challenges. The path towards the fusion of traditional design knowledge, with information-computational processes, generates multi-dimensional dynamics in which the physical world overlaps with the digital one. Thus, a blended panorama arises that requires a change in favor of a holistic approach, rather than declined on single aspects, intensely changing the production and organization processes of disciplinary knowledge.
In this scenario, the tools and methods of computational design that make use of artificial intelligence algorithms are spreading more and more, placing an amalgam between human intelligence and machines intelligence that proposes, as a result, something infinitely more prominent than pure sum between the parts. This has all the potential to produce a cultural and technological evolution in the project area that amplifies the intellectual powers of individuals with the results of the technology they have developed. It is an epochal transition for the design discipline itself, which undergoes a structural transformation starting from its conceptual foundations, evidenced by the need for an empirical

practice, augmented with a high concentration of knowledge to support the high intensity of the computer science.

It is evident that the technical possibilities offered by computational technologies, as often happens, not only have consequences attributable to the technical area. They intervene in thoughts, approaches, and generation of ideas determining new ways of defining things and their relations. Hence, digital technologies intervene substantially not only on the product-system, overwhelming the characteristics and structures of everyday products, but also on the methods and tools to "make" them, i.e. on the entire design process, raising critical questions about the ways design designs .

The transformation brought by digital tools on design practices and processes is based on a long path that originated in the 70-80s with the introduction of the computer-aided systems (CAD). The technologies available at the time rised a sort of revolution in the field of design, bringing significant advantages to "human designers" in representation and manipulation (Cantamessa et al., 2020). These are software tools that apply the principles of Euclidean geometry to the design environment through drawing, starting to build the instrumental basis of the link between numbers and shapes, between mathematics and design, which today takes on a strong relevance. CAD systems have spread precisely because of their ability to support human decisions in the field of design, with important repercussions also on product development and production. From that moment on, data and computer codes have entered the depth of the design process up to mature tools evolved into support systems that are no longer an exclusive aid to representation, but they find to affect the expressive language and, above all, the thinking of designers.

Generative Design systems (GD) works in a way that the projects are produced - independently or in collaboration with a human designer - by algorithms (McKnight, 2017) bringing out numerous reflections on the relationship between designer and algorithm, as well as on the opportunities and repercussions that these new systems have on the design process. Victor Papanek was already questioning how computer aided systems would have reduced design to an assembly of pre-packaged elements, prefiguring a condition of computer autonomy in design. Today the issue is infinitely more complex and disruptive, since the connective and combinatorial charge of digital tools generates new research areas in computational and generative design, in which artificial intelligence participates directly in the design processes.

With the increasing complexity designers need to orient themselves questioning the impacts of data revolution on practical tools and processes, on the extensions and contractions of the design space in these new contexts and the challenges that will derive from them (Cantamessa et al. 2020). The ever increasing weight (and made up of hyper-specific knowledge) that the technological-computational area assumes also seems to involve the sphere of problem solving increasingly entrusted to artificial intelligences, data and computing capacity, leading to ask "what kind of thinking is left to humans in innovation?".

Generative systems offer a real paradigm shift in design practice, in the design process, and in the material expression of the process. This change affects the interpretation that designers can give to artifacts and the actions that manipulate them, effectively shifting attention from singular objects and individual components to a holistic vision that interprets artifacts as systems and processes composed of interacting parts.

In this sense it is easier to understand that generative design processes have the potential to bring a wider cultural effect on design practices by bringing new methodologies but also - in the words of McCormack (2005) - new philosophies. Indeed, such holistic approaches can represent the basis for a change in product design process and approaches in general.

3. Generative Design Process

Generative Design (GD) has been rapidly developed and implemented in commercial softwares and applied in designing various kinds of products; starting from more complex ones such as aircrafts and automobiles, it quickly extends to architecture and objects of use. GD now refers to a series of software systems that exploit Machine Learning algorithms to autonomously recognize images, texts, or 3D models from which to formulate morphological proposals.

GD has been defined in different ways by scholars who approached the topic in their research from different angles: La Rocca (2012), for example, defines it as part of Knowledge-based systems, software applications capable of imitating human expert actions and automating the troubleshooting process. The design consequently oriented is based on precise and codified rules thus relieving the designers from the repetitive activities of the design process. In GD, a set of input values is applied to the product parameters, the system applies the rules and processes the inputs generating the project, with little or no human intervention (La Rocca, 2012).

Dhokia et al. (2017) refer to generative software as a set of tools to develop concepts starting from design requirements, constraints, and objectives, while Rodrigues et al. (2018) refer to real methods concerning generative design that use algorithms to produce a large number of design solutions or new alternatives within an environment governed by automated procedures.

Despite the different interpretations given over time to GD, most authors agree that it is a paradigm shift in the design process (La Rocca, 2012; Oh et al. 2018). Compared to previous computer-aided systems, the generative design process aims to ensure more efficient collaboration between artificial intelligence and the user-designer, using algorithms based on Machine Learning principles. This allows evaluating a large number of design hypotheses in a short time, to quickly optimize results according to needs and save resources, even by anticipating many evaluation phases at the beginning of the process through simulation.

It is an iterative design process, done by a designer and algorithms. Starting from the initial needs, the designer defines variables and constraints to formalize by returning them as input to the algorithm. The latter executes a large number of times the input by changing, according to a predetermined criterion, the values of the variables and consequently generating a certain amount of results. It is then up to the designer to analyze and evaluate the results of the calculation, possibly to learn new information from which to intervene on the definition of the variables and constraints to be established as inputs. The iterative process is precisely in the fact that the flow just described can be repeated until a product that meets the requirements is reached. The GD process can be described as follows (McKnight, 2017):

1. Set the design parameters and goals.
2. Generate designs with optimization under different parameters.
3. Study options, iterate, modify, and select the best design.
4. Manufacture the final design.

The GD software, therefore, acts just like a design assistant: the designer imposes requirements, based on which the software elaborates a series of proposals. Each proposal considers both the constraints set by the designer and other variables related to the material feasibility of the object. The designer who works with GD software is then required to evaluate the necessary materials, and the characteristics of the result he wants to obtain just before the constraints (i.e., in the ideation phase). Following the insertion of a whole range of information, the designer receives hundreds, if not thousands, of results perfectly consistent with what was expressed.

Hence, the final product will be the result of a "collaboration" (Goldschmidt, 2014) between the designer and the algorithm, capable of optimizing the relationship between form, function, and material. Thanks to the application of GD, it is possible to design products that are more efficient, more resistant from the early stages, and in which the optimized parts can meet specific needs and more sustainable optimization of the quantity of material forecast of the disassembly steps.

Moreover, the application of this process often results in projects that otherwise would not have been possible using the traditional design process, or certainly not in such a quantity and a short period of time.

The enormous potential of the generative design environment still increases gathering the progress made in the production processes like additive manufacturing and new materials which today allow the production, on small but also on a large scale, of models with complex and/or organic geometries that would have been difficult if not impossible to achieve with traditional production technologies. The new production processes allow to directly manufacture physical models through the data obtainable from the 3D model, layer by layer, stimulating nature-inspired Design for Additive Manufacturing.

https://doi.org/10.1017/pds.2022.181 Published online by Cambridge University Press

The reference to nature returns if we consider that the generative process refers to the ways in which nature generates its forms through growth and how optimizes the relationship between materials, form and performance; GD has proved to be a useful tool for designing products and components that use less material as possible, producing models that can be "grown" and modified like real organisms living, cellular or natural, renewing the close link between design and biomimicry. Hence, the advantages of GD are numerous in terms of time-saving and optimized design and industrial processes:

1. The possibility to analyze countless solutions to define the product.
2. Performance control.
3. Time and cost optimization regarding tests, simulations, verifications, materials, processes, and supply chain.

It would therefore seem that, as John Gero wrote in 1992, "Computer-aided Human designers will produce better designs".

4. Design intelligence & Artificial Intelligence

With Generative Design software, the design processes take on new paths, opening an overturning of the established design paradigm that evolves according to the necessary ability to know how to manage a large amount of specific information right from the preliminary stages of the project, actually changing the way product are designed.

Design intelligence merges with artificial intelligence giving life to an Intelligent Design that requires an evolution of the knowledge and skills traditionally required, not so much according to the role that artificial intelligence and the generative algorithm assumes. but concerning the role of the designer in the new process thus configured. We have reached a condition in which "We design processes to process designs" since the acceleration in the design and production processes brought about by new technologies, as well as allowing the reduction and optimization of time, phases, procurement of raw materials and product performance simulations, has to intervene on the knowledge and skills of the figures involved.

The traditional design process is divided into a phase of analysis and quantitative and qualitative data collection called the divergent phase, followed by a synthesis process in which possible solutions are identified and where the design agency resides. The process is repeated iteratively with a subsequent divergent phase to then converge in the definition of the preferred solution. It is in this last phase of definition that the design process connects more coherently with the production.

The diffusion of additive manufacturing production processes has undoubtedly offered designers greater freedom in the production of complex geometries (Lebaal et al., 2019), bringing substantial changes also in the knowledge necessary for design, in the approaches, in the tools, rules, and methodologies (Thompson et al., 2016).

In this context, questions about how the processes of design change in the face of the impacts of new technologies and tools arise, proponing new visions of the world and the things that populate it. Furthermore, the relationship between designer and generative algorithm stimulates reflection on the processes involved, regarding the technical, social and cultural environment of the project.

The first element of profound change in the traditional design process, therefore, lies in the fact that the proposals provided by the GD algorithms depend on the inputs entered; what is therefore important to understand is that this type of design, even before drawing shapes, designs rules and procedures by dividing the design challenge into interconnected sub-challenges.

Designing in these ways requires focusing on the processes that link the elements of the project and keeping them present in the design from the outset. The designers dealing with these new tools must identify the best solution among the many solutions proposed by the generative software based on different parameters, in a chosen path that must be known, understood, and governed.

Therefore, compared to the traditional design process which makes use of consecutive phases of divergent thinking and convergent thinking, in the DG, the two phases disappear: there is no analysis phase and consequently one of synthesis elaboration, but the synthesis phase precedes that one. of analysis.

In the collaboration between designer and algorithm, an Intelligent Design emerges which transforms the input values through an automatic and immediate analysis-synthesis phase in which the phase originally dedicated to the qualitative analysis and the signs of the definition of the artifact is overwhelmed by the generative process. In this new design context, there is a contraction of some operations and a great expansion of others, making the design process in the GD an essentially systemic process. For example, formal research takes place on a form already elaborated and defined by numerical parameters that the designer can alter. In this sense, design enters a phase of post-algorithmic design in which the treatment of the shape becomes a systemic action on the component and the product.

This allows the generative evolution of morphologies understood and interpreted as systems of relations between the parts in which the algorithm operates and simulates the new solutions in real-time, returning a profoundly changed approach to the project that considers all the parts or components of the project as interconnected elements, according to the logical, constructive, functional, productive link that binds them. This involves a change in favor of a more flexible approach where the designer's critical reflection process becomes increasingly important in a design framework in which a collaboration between designers, data and generative algorithms takes place, which takes into account people, the environment. and production constraints or opportunities, also bringing a new aesthetic language.

The designer who works with the GD must start from a complete set of information regarding the functions and performances required of the product, the stresses to which it will be subjected, the components and materials from which it will be composed, placing himself from a different angle on the design problem. Considering the product in its complexity and in the relationship between the parts makes up a hyper-system which, if on the one hand can allow designers to tackle highly complex problems (McKnight, 2017), on the other hand, gives the possibility to operate on models that in real-time respond by simulating dimensional, performance, energy, material and formal data.

The creation of a definitive model is the morphological solution that will go into production in which the formal study has taken on a more effective processing space both from an aesthetic and performance point of view. Therefore, Intelligent Design is not just computer-aided, it is digitally mediated design.

5. Conclusions

The development and dissemination of digital technologies have proposed new generative tools for design favoring the emergence of the "new world" of representation. World in which design must place itself and evolve, placing itself as a hinge between other disciplines and systems of knowledge. If it is true that technologies engage a dialogue with culture that modifies supports and manifestations, to make them inseparable it is also true that it is through design that the cultural system "materializes" and becomes socially active. According to this perspective, when design relates to digital technologies it means “designing the cultures of the future”, also concerning the design culture itself.

The use of generative tools has accelerated this change to a larger extent, demonstrating that GD cannot replace the human designer, but that instead, designers and AI can become partners in the design process by working collaboratively (Goldschmidt 2014).

The algorithms of generative design create in a very short time thousands of possible solutions for a product based on criteria and objectives established by the designer, who at this point "only" has to make a choice. However, where the morphological development occurs through an algorithm that provides a series of variants based on a given input, then it is the design “DNA” that changes radically.

The creation of intelligent models offers the designer the possibility of having the digital twin on which to simulate technical and behavioral data, the maintenance and decommissioning phases, and also the opportunities for implementation and redesign of the product. The digital model on which the morphological evolution takes place is one of the strategic elements on which the company will make the next choices, will test the market in time, and will give the possibility to define the production and sales phases in advance. Therefore the digital model does not respond only to technical and technological needs but also as a forecasting element in determining the business capacity of a brand.

In summary, therefore, the main differences between traditional design and generative design are:

1. in the time of conception
2. in the number of proposals generated in a given time
3. in the optimization according to the technological, typological, and productive constraints;
4. in the possibility of making design changes even at an advanced stage, appreciating the effects through simulation
5. in the order and type of activity of which the design process is composed.

The advent of computational and generative tools does not envisage the role of the designer as a passive user of the process, but certainly places him in front of an inevitable evolution to an ever greater familiarity with the use of codes for the design of constantly evolving products. and an ability (and flexibility) to work on structures, processes, rules, and interactions.

There is therefore a strong synergy between the designer and the artificial intelligence algorithm of generative design which, through a different but still iterative process, together with reach the best possible design solution among all those generated.

In generative design, the focus shifts from the result to the process, bringing the designer's attention to process control: the model is no longer the goal of the project but is the terrain for experimentation, study, and verification.

Today, product design has entered a new era, in which the potential of digital technologies in connecting humans and machines within new industrial environments involves a new configuration of the design landscape.

With Digital Transformation, new technologies trigger potential processes of innovation and remodeling at the structural and organizational level of the entire manufacturing sector. The transformation acts in-depth both on the design culture and the company culture.

In this sense, the challenge posed to contemporary designers falls on a critical understanding of the tools available, on their careful declination and implementation. Guiding and controlling the different phases of product development - from the creative to the realization.

Hence, If it is true that "it is not possible to discuss industrial design referring to epochs before the industrial revolution", digital transformation necessarily induces us to rethink the new instances of industrial design facing the opportunity to create a symbiotic balance between artificial intelligence and design intelligence.

References

Caetano, I.; Santos, L.; Leitão, A. Computational design in architecture: Defining parametric, generative, and algorithmic design. *Front. Arch. Res.* 2020, *9*, 287–300.

Cantamessa, M., Montagna, F., Altavilla, S., & Casagrande-Seretti, A. (2020). Data-driven design: the new challenges of digitalization on product design and development. *Design Science*, *6*.

D.W. Rosen A review of synthesis methods for additive manufacturing Virtual Phys. Prototyp., 11 (4) (2016), pp. 305-317

D.W. Rosen Research supporting principles for design for additive manufacturing Virtual Phys. Prototyp., 9 (4) (2014), pp. 225-232

Dhokia, V., Essink, W. P., & Flynn, J. M. (2017). A generative multi-agent design methodology for additively manufactured parts inspired by termite nest building. *CIRP Annals*, *66*(1), 153-156.

Goldschmidt, G. (2014). *Linkography unfolding the design process*. Cambridge, Massachusetts: MIT Press.

Kennedy, E., Fecheyr-Lippens, D., Hsiung, B. K., Niewiarowski, P. H., & Kolodziej, M. (2015). Biomimicry: A path to sustainable innovation. *Design Issues*, *31*(3), 66-73.

La Rocca, G. (2012). Knowledge based engineering: Between AI and CAD. Review of a language based technology to support engineering design. *Advanced engineering informatics*, *26*(2), 159-179.

Loy, J., & Novak, J. I. (2021). The future of product design education Industry 4.0. In *Research Anthology on Cross-Industry Challenges of Industry 4.0* (pp. 1666-1685). IGI Global.

M.K. Thompson, G. Moroni, T. Vaneker, G. Fadel, R.I. Campbell, I. Gibson, A.Bernard, J. Schulz, P. Graf, B. Ahuja, F. Martina Design for Additive Manufacturing: trends, opportunities, considerations, and constraints CIRP Ann., 65 (2) (2016), pp. 737-760

Magistretti, S., Dell'Era, C., & Petruzzelli, A. M. (2019). How intelligent is Watson? Enabling Friedman, K. (2003). Theory construction in design research: Criteria: Approaches and methods. *Design Studies*, *24*, 507–522.

Maglic, M. J. (2012). Biomimicry: using nature as a model for design.
Matthew McKnight, (2017), ”Generative Design: What it is? How is it Being Used? Why it’s a Game Changer!,” in *The International Conference on Design and Technology*, KEG, pages 176–181. DOI 10.18502/keg.v2i2.612
Meyer, M., Wiederkehr, I., Koldewey, C., Dumitrescu, R. (2021) ‘Understanding Usage Data-Driven PrIoCdEucDt 2P1lanning: A Systematic Literature Review’, in *Proceedings of the International Conference on Engineering* 1 *Design (ICED21)*, Gothenburg, Sweden, 16-20 August 2021. DOI:10.1017/pds.2021.590
N. Lebaal, Y. Zhang, F. Demoly, S. Roth, S. Gomes, A. Bernard Optimised lattice structure configuration for additive manufacturing CIRP Ann., 69 (1) (2019), pp. 117-120
Rodrigues, E., Soares, N., Fernandes, M. S., Gaspar, A. R., Gomes, Á., & Costa, J. J. (2018). An integrated energy performance-driven generative design methodology to foster modular lightweight steel framed dwellings in hot climates. *Energy for sustainable development*, *44*, 21-36.
S. J. Oh, Yongsu Lee, Ikjin Kang, Namwoo, “Deep Generative Design: Integration of Topology Optimization and Generative Models,” *Journal of Mechanical Design*, 2018.
Standard A., 2012. Standard terminology for additive manufacturing technologies, ASTM International F2792-12a.
T. Vaneker, A. Bernard, G. Moroni, I. Gibson, Y. Zhang Design for additive manufacturing: framework and methodology CIRP Ann., 69 (2020), pp. 578-599
Tavsan, F., & Sonmez, E. (2015). Biomimicry in furniture design. *Procedia-social and behavioral sciences*, *197*, 2285-2292.
Teresko, J. (1993). Parametric Technology Corp.: Changing the way Products are Designed. *Industry Week, December 20*.
Volstad, N. L., & Boks, C. (2012). On the use of Biomimicry as a Useful Tool for the Industrial Designer. *Sustainable Development*, *20*(3), 189-199.
Wang, Z., Zhang, Y., & Bernard, A. (2021). A constructive solid geometry-based generative design method for additive manufacturing. *Additive Manufacturing*, *41*, 101952.
Y. Xiong, P.L.T. Duong, D. Wang, S.-I. Park, Q. Ge, N. Raghavan, D.W. Rosen Data-driven design space exploration and exploitation for design for additive manufacturing J. Mech. Des., 141 (10) (2019)