Data-Driven Generative Design Integrated with Hybrid Additive Subtractive Manufacturing (HASM) for Smart Cities

Savas Dilibal, Serkan Nohut, Cengiz Kurtoglu, and Josiah Owusu-Danquah

Abstract Generation of smart cities that considers environmental pollution, waste management, energy consumption and human activities has become more important in recent years since it was first introduced in the 1990s. In the smart cities, most of the structures, machines, processes and products will be redesigned in terms of technological developments linked to the fourth industrial revolution, Industry 4.0. This situation introduces the need of new design models that address extended significant parameters for manufacturing. Data-driven generative design methodology is an algorithmic design approach for developing state-of-the-art designs. Generative design may give the decision-makers more sustainable optimized project solutions with the iterative algorithmic process. Many parameters and constraints can be taken into consideration during the designing process, such as lightness, illumination, solar gain, durability, cost, sustainability, mass, factor of safety, mechanical stresses, resilience etc. In the generative design, an iterative process occurs via cyclic algorithm from ideation to evaluation to reveal possible potential design solutions. The increase in design freedom and complexity boosts the importance of new generation manufacturing methods. Hybrid additive subtractive manufacturing (HASM), a key component of Industry 4.0, offers tailored and personalized production capabilities by combining additive and subtractive processes in the same production

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unit. In today's digital era, there is a growing need to create an integrated data-driven digital solution which consists of a multidisciplinary functional design integrated with hybrid additive subtractive manufacturing. Generative design integrated with hybrid additive subtractive manufacturing approach offers creating functional multi-criteria-based product combinations with sustainable organic mechanisms for engineering purpose. Alternatively, this approach provides dozens of different solutions for their studies considering multi-criteria, such as determining the convenient sunlight angles for walkways, computing optimum dimensions of smart structures, enabling transportation vehicles to pass underground or bridges etc. The main objective of this chapter is to introduce the importance of generative design and hybrid additive subtractive manufacturing for smart cities and present the critical advantages of a data-driven generative design concept algorithm integrated with hybrid additive subtractive manufacturing approach that will increase the speed of transition to smart cities. This chapter discusses a concept that integrates hybrid additive subtractive manufacturing with a data-driven generative design for the reliable, cost effective and sustainable design of components that can be used for establishment of secure smart cities. After conceptual explanations, the main aim and advantages of the concept are realized by a case study which is about the design of a drone chassis. A drone chassis is selected as a case study since drones will be used extensively for mainly security and logistics purposes in smart cities and design of drone chassis can be optimized by the proposed concept.

Keywords Data-driven algorithms · Generative design · Generic model · Computational design · Smart manufacturing · Hybrid additive subtractive manufacturing · Drone chassis · Smart drones · Secured smart cities · Industry 4.0 · Internet of Things (IoT)

1 Introduction

Rising urban populations around the globe places a huge demand for smart city design concepts that address the issues of safety and beauty of built infrastructure and account for multiple stakeholders related to efficiency, energy conservation, resilience and long-term sustainability [1]. This design paradigm rests on creation, accessibility and usability of digital platforms with infinite data from almost every element that constitute our cities, including humans and the built infrastructure [2]. Establishment of smart cities include automatic collection and analysis of huge amounts of data that will be enabled by the main aspects of Industry 4.0 (e.g. Internet of Things (IoT)) [3–5]. Therefore, the concept of smart cities and Industry 4.0 should be considered together [6]. For example, cloud computing, that can be defined as storing, accessing and analyzing data through programs and models to make decisions over the Internet will be a critical on-demand service for increasing the quality and performance of urban services in smart cities. With the use of IoT, billions of devices will generate data in smart cities and send them to the cloud [7]. Lom et al.

[8] reported that although Industry 4.0 and smart cities have different terminologies, that have a lot in common in terms of Internet of Things (IoT), Internet of Energy (IoE), and Internet of People (IoP).

The data that is collected through data digitization introduced by Industry 4.0 will enable innovative improvements in more efficient, cost effective and collaborative design, manufacturing and servicing (e.g., transportation) processes in addition to traffic, pollution, waste and safety management in smart cities. The generative design concept is one of the pioneering concepts that shows enormous potential to be used in smart cities. Various definitions of generative design can be found in literature [9]. Some design algorithms that mimic nature can be accepted as the starting point of generative design in literature [10]. In its simplest form, it can be defined as an algorithm-based design process to assist exploring multiple design variants. The main principle of generative design is to create a large number of designs depending on the user constraints and design parameters and to offer a number of alternative solutions which overlap with the goals [11]. Engineers, architects and designers import the restrictions to create the iterative algorithms that reveal the most efficient design through making geometric syntheses. Light-weighting strategy in design with an optimal shape emerged topologically optimized design solutions. Different from this strategy, generative design methodology offers varied options for modern engineering and architecture projects with multi-objective optimization. In the generative design process, designers give the final decision after receiving design options from an iterative process of generative design with the combination of many effective design parameters related to the geometry, material, load cases, stiffness, manufacturing method etc. Generative design algorithms are applied in different areas such as in design of health instruments, automotive, aerospace or construction [2, 12]. These concepts strongly integrate computational modelling and digital innovations tools that foster designs addressing long-standing urban challenges. Obviously, the traditional use of Computer Aided Design (CAD) tools, which often require too much time and effort to modify design models or even treat some of these models as disposable when changes are needed, do not suffice in this novel design concept.

In the establishment of smart cities, ability to manufacture tailored and complex designs is as important as generating improved designs. The generative design method reveals very advantageous design options by offering hundreds or thousands of possible solutions in a relatively short time that cannot be performed by a human designer. However, traditional manufacturing methods may alone have limitations for the production of proposed designs [13]. Furthermore, high manufacturing costs, high material waste and requirement of several machines in several stations in traditional manufacturing methods do not comply with the principles of smart city concept. Additive Manufacturing (AM), one of the main technologies of Industry 4.0, offers cost-effective production of personalized and complex-shaped forms [14]. Therefore, using additive manufacturing methods can increase the level of design freedom especially for complex designs. Although additive manufacturing does not have to always be the preferred serial manufacturing method of complex designs nowadays, recent developments show that 3D printing technologies will offer serial production at low costs in the near future.

Most additive manufacturing methods can be used nowadays to produce a limited part size. A novel manufacturing concept, the so-called Hybrid Additive Subtractive Manufacturing (HASM) can enable production of large-sized components. As an extension of additive manufacturing, hybrid additive subtractive manufacturing includes the addition and subtraction (secondary processes like milling, drilling or surface enhancement) of material in the same machine to improve the dimensional accuracy, mechanical/physical properties and microstructure of the printed parts [15]. Furthermore, using more than one type of materials on the same part with higher degree-of-freedom and expected isotropic-anisotropic material properties will also be possible by hybrid additive subtractive manufacturing. Thus, the integration of hybrid additive subtractive manufacturing to generative design processes can enable the consideration of hybrid additive subtractive manufacturing process parameters especially for personalized and tailored end products [16].

This study discusses the generative design integrated with hybrid additive subtractive manufacturing approach that prepares print-ready design solutions suitable for the hybrid additive subtractive manufacturing processes. As a case study, generative design of a chassis for a drone is performed and some solution designs is analyzed in terms of their suitability for hybrid additive subtractive manufacturing. A drone example is selected since drones will play a vital role in varied applications functioning in traffic, population and natural disaster monitoring and management, smart logistics and transportation in smart cities.

First of all, state-of-the-art for generative design and hybrid additive subtractive manufacturing is provided with up-to-date studies from the literature. Next, generative design approach and its current applications is mentioned. After that, the importance and place of generative design and hybrid additive subtractive manufacturing for the establishment of secured smart cities is explained. The concept that integrates generative design and hybrid additive subtractive manufacturing is explained with details by providing the schematic representations that simulate the main principles. Finally, the design of a drone chassis is investigated in the framework of the proposed concept.

2 Generative Design Approach

For complex multicriteria design problems, generative design approach is most viable. Generative design utilizes software algorithms that allow designers to very quickly produce, explore different concept alternatives and optimize several sample models to make informed decisions regarding design problems [17]. For the components that have an existing geometry, topology optimization is a suitable method however for the designs that are not defined, the more advanced/recent generative design methods incorporate artificial intelligence (AI) capabilities that try to reproduce aspects of human design processes [18]. The design, and consequently the model, evolves from a chosen concept and it is iterated until a final outcome is achieved. This method permits the variation of design parameters randomly within predefined limits to and provides possible design solutions with respect to manufacturing process and multiple constraints such as manufacturing cost and geometric suitability [12].

Schematics of Fig. 1 describes the integrative process of generative design methodology. Although the computational software used in this process plays a cardinal role in the design, there is still the need for a human expert, so-called decision maker, to explore, modify, evaluate and select the final design outcome. The requirements, objectives and constraints of the project are pre-determined (in the abstraction stage) and entered into the program by the designer at the initiation stage. The generative design program produces designs in a short period of time, and several of these options are analyzed, sorted or ranked based upon appropriate design metrics such as safety factor, weight, mechanical stresses etc. The generation of varied design options is done through the algorithm(s), and usually the print-ready design solutions can be used via digital additive manufacturing workflow. With guidance of an engineer or designer, solutions from the software are presented with an optimal design with corresponding data that will be useful during the design selection [2, 19, 20]. Depending on the scope of application, the computational technique that underline the design automation process (i.e., rule algorithm) may use either one or a combination of the following.

- Shape Grammars (SG),
- Lindenmayer Systems (LS),
- Cellular Automata (CA),
- Swarm Intelligence (SI)
- Genetic Algorithms (GAs).

Details of these techniques have been presented in the work of Gu et al. [21] and various applications of real and binary coded GAs, Multi-objective GAs, Parallel GAs, Chaotic GAs, Hybrid GAs have been demonstrated in literature [22–24]. Genetic algorithms that are inspired by the biological evolution process is the most

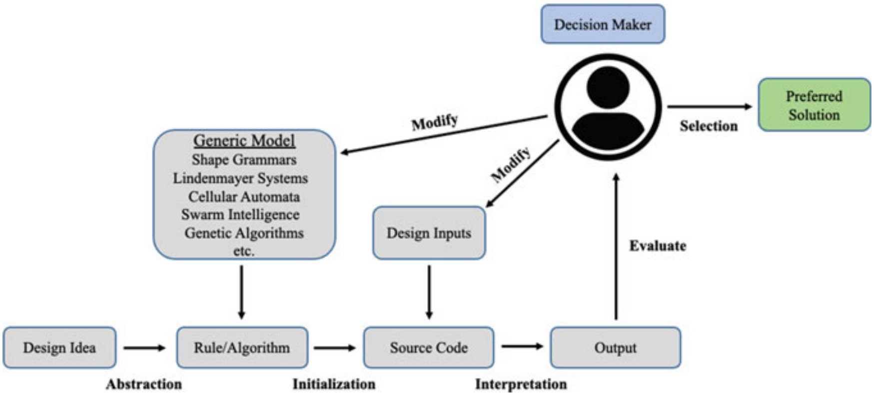

Fig. 1 Typical flowchart describing generative design method

dominant method amongst them. In GAs, an initial set of solutions is created, and an optimum solution is reached through continuous iterations [23]. The main operations in the iteration process are shown in Fig. 2.

The general concept of genetic algorithms is demonstrated in Fig. 2. Initially, a randomized design population is generated (based on input design parameters) and is tested according to fitness/design criteria. New population is created using crossover and mutation operations and evaluated until the fitness criteria are satisfied. The process continues until optimum conditions are met and the best solution(s) is/are selected. This is analogous to the natural evolution process which ensures that the weakest creatures are removed from the population or are not reproduced.

One of the important steps in the genetic algorithm is the selection step, i.e., determining the best individual(s) from the current design population to participate in the next cycle of mutation or crossover cycle. Examples of the selection techniques used over the past years in genetic models include roulette wheel, rank, tournament, Boltzmann, and stochastic universal sampling [24]. In the crossover operation, new

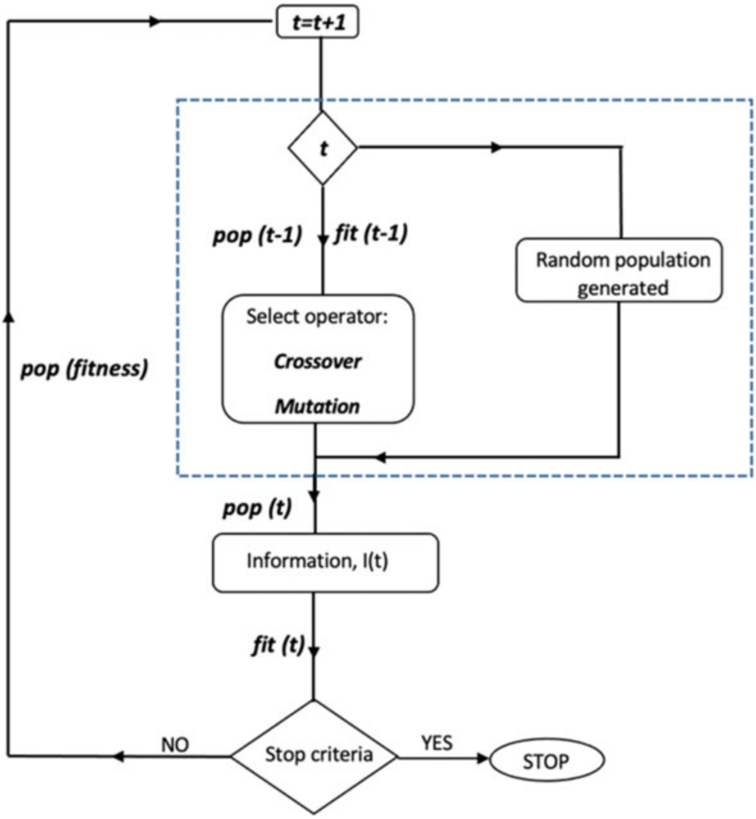

Fig. 2 General concept of genetic algorithm

offspring or population is generated by exchanging viable genetic information of two or more parents (from the previous population); on the other hand, mutation operators ensure the existence of genetic diversity between populations. An effect of mutation operators is the continuous distinctiveness in the solutions between generations. Single point, two-point, K-point and uniform crossover operators are simple and easy to implement, but the most widely used option is the partially matched crossover which is known to have a better convergence rate with lesser likelihood of loss of information from one generation to the next. Displacement mutation, inversion mutation and scramble mutation are the most common mutation operators. The work of Goldberg and Holland [25] revealed the difference of genetic algorithms from traditional algorithms. The genetic algorithms work through the software code of the parameter set instead of the parameters. In addition, genetic algorithms use probabilistic transition rules instead of deterministic rules.

3 Generative Design Applications

Generative Design is a modern tool that automates the computer-aided design process through multi-parameter optimization with regard to parameters, limitations and constraints defined by the designers. The advantages offered by generative design will definitely expand its usage areas in the future. Generative design applications have been started in architecture but nowadays can be seen in different fields such as construction and aviation [26–29]. Recently, some CAD commercial software introduced generative design tools in separate modules. The collaboration of human and machine offers superior design capabilities in different fields in industry. It has been rapidly adopted in the aerospace and defense industries [30]. NASA used artificial intelligence-driven generative methodology to design potential satellite antennas configurations [29, 31]. It is proved that the co-designer effort with artificial intelligence satisfies various project goals.

For decades, architects in the construction industry have been using scripts to take 3D design geometries created on computers. Design solutions that are revealed by a team of experts for projects, spending hours and days, can be considered as a waste of time, as well as cost. Designing and developing in a computer environment became easier with the help of commands, and this took the entire construction industry to a new way. With the parametric modeling and design automation methodology, a new generation of architectural designs and construction methods was revealed [32, 33]. Traditional design architectural modeling and parametric design software is emerging as a next step, computational modeling, scripts, and simulation engine, using the architects or engineers design defines the result of the entire process for creating the geometry. To illustrate this, it can be assumed as creation of the desired number of windows on a floor for a building model and evaluation of sunlight-receiving zones per unit length. This method can be considered as an advanced step in design optimization. An innovative approach that supports all design processes in the architecture and construction industries, taking into account the goals and constraints, the distribution of interior architectural structures created by generative design.

The generation, evaluation and evolution steps of a generative design process of an architectural project is shown in Fig. 3 as an example. The evaluation is carried out according to criteria defined by the designer such as interconnectivity, daylight and views to outside etc. According to given parameters, many possible design solutions can be generated within a short time as given in Fig. 3. The designer will have more freedom while selecting the best design from a large number of possible solutions or the generative design process can be repeated by changing the constraints.

In Fig. 4, an example of an architecture design offered by generative design is represented. For each design, it is shown how much these designs meet the criteria. It is clearly seen that many possible solutions that meet different criteria at different rates can be obtained by generative design method. After this step, the decision is made by the designer.

Important developments in manufacturing and design processes in the aerospace sector, such as weight reduction of outputs, environmental friendliness for fuel consumption and cost reduction, are gaining momentum with productive design. It is possible to convert the assembly process into one part by reducing the weight of components, which is an issue that spends significant time and cost in the automotive

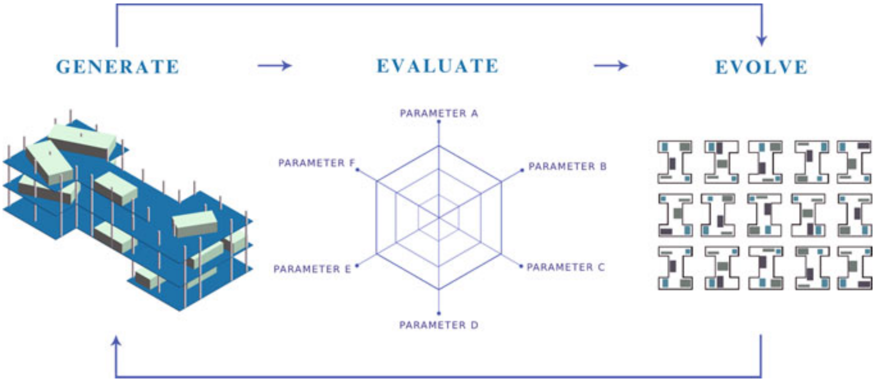

Fig. 3 Principle of generative design for architecture

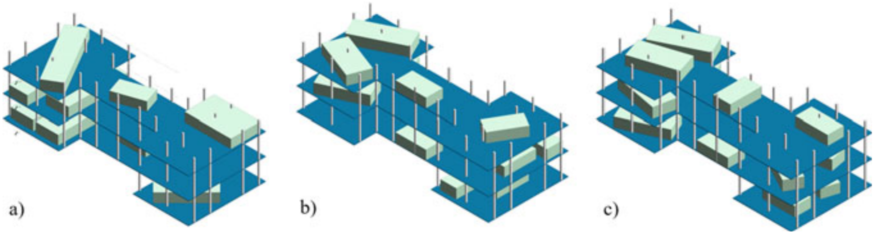

Fig. 4 Three potential layout solutions using generative design approach in architecture

industry, with productive design. In this regard, the development of layered manufacturing methods has a huge impact. With generative design, novel designs have been revealed in remarkable applications in the aviation sector [34]. Autodesk and Airbus designed their first bionic compartment produced using additive manufacturing technology integrated with generative design. This particular compartment, fixed between the passenger seating area and the aircraft's kitchen, is a partition wall that in some seating configurations will be used to support the reinforcement seats used by cabin crews during takeoff and landing. This powerful component is a component for aircraft manufacturers that they want to minimize its weight while maintaining infrastructure security. It is designed from the start with a generative design approach. The final compartment is created with 45% (approx. 30 kg) lighter than the existing designs, making it a significant development for aviation industry where less weight equals less fuel consumption. In the automotive sector, it is possible to convert the assembly process into one part by reducing the weight of components, which is an issue that takes significant time and cost. The development of this design process has a huge impact on the fact that additive manufacturing technologies give great flexibility to manufacturing methods and make it possible to produce parts with complex structures [35, 36]. In generative design, seven different parts can be converted into a single component via producing a lighter and stronger part in the automotive manufacturing sector. Reducing the weight of parts in the first step is of considerable importance for the automotive industry, considering that it increases consumption and performance. The ability to convert parts into a single component reduces both supplier chain costs and eliminates the loss of time and energy in the assembly process.

4 Hybrid Additive Subtractive Manufacturing and Generative Design for Smart Cities

There are mainly three fundamental manufacturing technologies which are formative manufacturing, subtractive manufacturing and additive manufacturing. In formative manufacturing, the final geometry is given via molding, casting, and shaping process. In subtractive manufacturing, the finalized geometry is created through machining (e.g., milling, drilling, turning etc.) processes. Different from these conventional manufacturing processes, the additive manufacturing process consists of implementation of layer-by-layer production to establish final product geometry [37]. Nowadays, the virtual models which are developed in CAD software can be transformed into the physical products for smart cities. The data-driven workflow starts from the designing procedures and followed by data-driven manufacturing technologies. An original computer-aided design (CAD) data is utilized to start the additive manufacturing process. The CAD file should then be converted to the standard .STL file format which is adopted by the additive manufacturing systems.

Additive manufacturing gives high design freedom to manufacture complex or freeform geometrical products. The early use of additive manufacturing techniques had limited material capability in the feedstock subsystem. However, metals [38], polymers [39], ceramics [40] and even composite materials can be utilized as a feedstock material in novel additive manufacturing techniques [41]. In recent years, nickel-titanium shape memory alloys [42–44] based 4D products are also manufactured using electron beam melting additive manufacturing technologies [45, 46]. Depending on the applied additive manufacturing technique, the manufacturing parameters, technical sub-processes, feedstock materials might be different. Additionally, different heat source technologies such as laser-beam, electron-beam can be used in additive manufacturing technologies for increased production capabilities [47].

The traditional hybrid subtractive manufacturing technologies such as combinations of milling/laser cutting/electric discharge machining, and sheet metal forming are commonly used in industry. An evolutionary development is adopted with the innovation of hybrid additive subtractive manufacturing. The hybrid additive subtractive manufacturing technology combines additive manufacturing with the subtractive manufacturing in order to improve physical properties and/or mechanical properties of the manufactured components with higher structural accuracy. Specific examples include integration of Laser Melting Deposition (LMD) into 5-axis CNC machine system [48], integration of Gas Metal Arc Welding (GMAW) into CNC milling machine [49]. The working principle of hybrid additive subtractive manufacturing is shown in Fig. 5.

Hybrid additive subtractive manufacturing will enable the use of different materials for different sections of a structure. The use of combination of two or more materials as a feedstock enables production of functionally gradient components through the hybrid additive subtractive manufacturing solution. Multi-material dependent parameters can offer advanced hybrid additive subtractive manufacturing initiatives

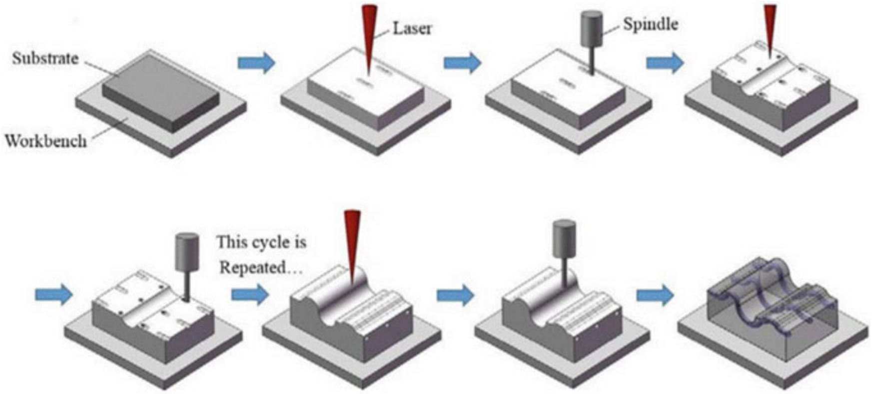

Fig. 5 Schematic representation of Hybrid additive subtractive manufacturing concept. This figure has been reproduced with permission from Elsevier [50]

to develop application-based functional products. Multi-material segments, such as metal-metal or metal-polymer, can be added into the single material parts to build material gradient structures [51]. In addition to the multi-material, the potential combination of hybrid additive subtractive manufacturing can enhance manufacturing degree of freedom for the production of complex components via combining the layer deposition pattern with machining. Multi-axis hybrid additive subtractive manufacturing process enables additional degree of mobility by minimizing kinematic constraints. Many complex components can be manufactured without requiring any support structure. In addition, inclusion of more degree of freedom to additive manufacturing through hybridizing with subtractive methods will decrease the production time by elimination of some setup changes [52]. Furthermore, the final product size can be enlarged using the hybrid additive subtractive manufacturing technology in different fields with a continuous digital production line for large-scale products [53]. Improved mechanical properties can also be achieved by using hybrid additive subtractive manufacturing [54]. For example, the potential anisotropy in mechanical properties in the build direction is another significant characteristic for the hybrid additive subtractive manufacturing. The anisotropy can be mitigated with a well-defined hybrid additive subtractive manufacturing processes in some specific cases. A deliberately desired anisotropic structure can be established via creating a built orientation in the desired plane. In addition to the above-mentioned advantages, the hybrid additive subtractive manufacturing processes can be used in the component defect repairing process [55]. In many industrial applications, repairment is preferred for the budget and time management rather than complete reproduction. In this case, the component can be repaired via hybrid additive subtractive manufacturing instead of fully re-producing.

Sustainability will be one of the most important concerns in the development of smart cities. This will bring the need of sustainable manufacturing methods in order to produce components of smart cities. Hybrid additive subtractive manufacturing will offer eco-friendly designs with sustainability since it will reduce the need of energy and material usage. Furthermore, unlike traditional manufacturing methods where the same parts are produced, hybrid additive subtractive manufacturing allows a high degree of design freedom so that personalized structures with complex designs can be achieved. Hybrid additive subtractive manufacturing offers also great benefit for production on storage of spare parts and reduction of repair times with on-site and on-time production. On-site and on-time production means production of any spare part when it is needed. With developments in on-site and on-time production with hybrid additive subtractive manufacturing, the inventories of spare parts and distribution logistics will be reduced, and this will provide cost efficient and ecological manufacturing processes. Final products can be produced in a hybrid additive subtractive manufacturing process via reduced sacrificial surface and increased dimensional accuracy. The additive manufacturing concept has started with polymeric materials but nowadays it is possible to use this method for metals and ceramics [56, 57]. With the developments in hybrid additive subtractive manufacturing, the advantageous properties that are summarized above will make great contributions in manufacturing processes in smart cities. Therefore, hybrid additive subtractive manufacturing will play a vital role in smart cities.

Generative design will not only be used in order to improve/upgrade the currently used designs but will also bring new design options by using artificial intelligence and more data compared to topology optimization. These new designs will be performed in engineering as well as in architecture. The designers will be able to input many parameters, criteria and constraints into a data-driven generative design algorithm so that suitable designs will be generated from the beginning of the design process. Furthermore, integration of generative design algorithms with real-time data collected by using some sensors will enable more realistic design updates according to changing conditions with time. During the design of structures and machines for which mass is of importance for energy use, optimization of weight in generative design will provide less CO_2 emissions and more sustainability. Since automatic generative design will offer a cost-effective designing process and more freedom to the designers, it will be one of the most important manufacturing concepts in smart cities. Use of generative design in smart cities should not be limited to manufacturing. Transport infrastructure will be another application area of generative design where many possible solutions can be provided by taking into account many criteria such as population intensity, topography and transportation lines etc.

5 Generative Design Integrated with Hybrid Additive Subtractive Manufacturing

As it is stated above, both hybrid additive subtractive manufacturing and generative design will gain great importance in establishment and improvement of smart cities. In this section, integration of generative design with hybrid additive subtractive manufacturing concept will be introduced and the possible advantages will be discussed in terms of concerns related to smart cities. In principle, integration of the hybrid additive subtractive manufacturing with the generative design will allow considering the hybrid additive subtractive manufacturing-based parameters from the beginning of the design process.

Generative design offers different optimized complex shaped customized model solutions for production. The complexity of the created models can cause various difficulties for the production in traditional manufacturing technologies. The additive manufacturing technologies provide suitable solutions for the mass production of complex shaped parts for industrial scale applications. Generative design can be suited for highly customized mass production through integrated hybrid additive subtractive manufacturing technologies. The refinement and readiness of the generativity optimized design for additive manufacturing are the important parameters for processing. The selected additive manufacturing process affects the quality of the final product. An optimized additive manufacturing process solution is required for reducing potential residual stresses and distortions during melting and re-solidification of the layers. Furthermore, build orientation, laser focus/path, support structure, manufacturing speed and time are the main effective parameters during the additive manufacturing process. The additive manufacturing process connects print-ready design solutions with the additive manufacturing and traditional computer numeric control (CNC) machining for the final products. In some commercial generative design tools, it is possible to select additive manufacturing as a production method so that many design options suitable for Fused Filament Fabrication (FFF) can be created. However, only limited parameters regarding additive manufacturing are given as input to the data driven algorithms and more advanced integrated additive manufacturing tools should be also adopted to consider additive manufacturing-based constraints during the optimization process.

In recent years, inclusion of additive manufacturing to conventional subtractive methods (e.g., milling, turning, drilling etc.) has become popular in order to improve the quality of the products and make additive manufacturing economically competitive for large volume serial production. The hybridized method that includes a combination of additive and subtractive activities in one production line is called Hybrid Additive Subtractive Manufacturing [58]. An example would be combining a multi-functional (multi-tasking) CNC machine tool and AM module. Hybrid additive subtractive manufacturing offers advantages in cost effective and flexible repair, surface finish, machining precision, addition of difficult features and multi material 3D printing over additive manufacturing methods [59].

The hybrid additive subtractive manufacturing process integrated with the digitally print-ready generative design solutions can provide many advantages for the customized mass production. The hybrid additive subtractive manufacturing technologies integrated with generative design will allow engineers and architects to easily produce varied generatively designed optimized complex components [60–63]. For instance, soft robotics is one of the trending technologies in robotics. In soft robotic technologies, multi-material-based hybrid additive subtractive manufacturing processes offer novel design solutions. A full integrated design and hybrid additive subtractive manufacturing package can give state-of-the-art soft robotics model solutions for industry. The rise of generative design integrated with hybrid additive subtractive manufacturing may enable novel solutions in smart cities and factories. Recent development in generative design offers optimum solutions manufacturing constraints and design objectives.

In order to obtain the full advantages of generative design integrated with additive manufacturing, a hybrid manufacturing concept should be adopted to generative design algorithms. Instead of a pure additive manufacturing process, the hybrid manufacturing concept will contain the supplemental additive and subtractive technologies and offer advantages explained in the previous chapter. In classical ways, after a design is selected among many designs generated by generative design algorithms, compatibility of the design to selected hybrid additive subtractive manufacturing method should be evaluated by the designer or the manufacturing engineer. The flow chart of such two discrete processes is shown in Fig. 6.

As the preferred solution selected by the decision maker from many possible design solutions created by generative design process will be produced by hybrid

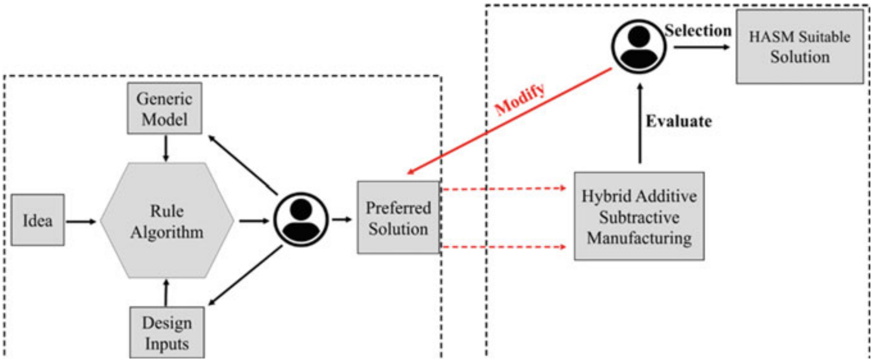

Fig. 6 Generative design and hybrid additive subtractive manufacturing as two discrete processes

additive subtractive manufacturing, its suitability has to be checked by the designer. If it is not suitable for hybrid additive subtractive manufacturing, the designer should select another design. This loop will continue until a design suitable for hybrid additive subtractive manufacturing is obtained. This transitions between two boxes given in Fig. 6 maybe in most cases waste of time and energy. The hybrid additive subtractive manufacturing concept can be incorporated into state-of-the-art projects with any generative design software that offer print-ready solutions as shown in Fig. 7. In this proposed concept, the criteria related to hybrid additive subtractive manufacturing can be given as input to generative design algorithms and design solution suitable for the hybrid additive subtractive manufacturing can be obtained.

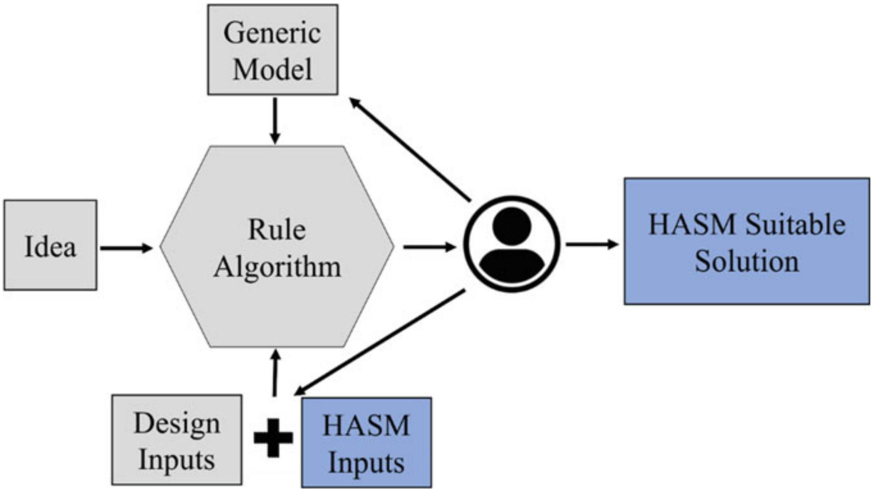

Fig. 7 Generative design integrated with hybrid additive subtractive manufacturing

Since a hybrid additive subtractive manufacturing is integrated, in addition to the parameters regarding the selected additive manufacturing method, the parameters related to subtractive method will also be taken into account. Integration of hybrid additive subtractive manufacturing with generative design will not only eliminate designs that are not suitable for hybrid additive subtractive manufacturing method, but also more flexibility and freedom will be provided during the selection of best design as a result of advantages offered by additive manufacturing.

In this novel design process, the design functions $\boldsymbol{p_i}$ that affect the final product $\boldsymbol{P}$, are selected to include those required from the additive manufacturing (see Eqs. (1a) and (1b)). One can represent this structure as:

$$P = p_1 \times p_2 \times p_3 \times p_4 \times \cdots \cdot p_n \tag{1a}$$

$$P = \prod_{i=1}^{n} p_i \tag{1b}$$

where, p_i is an objective function representing the individual design considerations such as cost, materials, functional performance etc. which affect the final product. These functions can be individually dependent on intrinsic design variables and can have constraints/limits, c_{j} in their range of values (see Eqs. 2a, 2b).

$$minimize/maximize : p_i \tag{2a}$$

$$\text{subjected to: } c_j\left(p_j\right) \leq 0,\ j = 1, 2, \ldots, c \tag{2b}$$

$$\text{with bounds: } p_i^L \leq p_i \leq p_i^U i = 1, 2, \ldots, n \tag{2c}$$

In such multi-objective optimization designs, equality and inequality constraints are needed to reduce the computational time and give more accurate results. Some of the objective functions must be minimized or maximized to control the outcome of the iteration process; for example, while minimizing the cost, the functional performance must be maximized in the case of the hybrid additive subtractive manufacturing process shown in Fig. 7. The obvious objective is to establish a set population or solution that satisfies all/most of the constraints as much as possible.

In the generative/optimization process, the population of structures (or design outcomes) is modified at the end of each iteration, and the information (I) about the adaptation of phenotypes are used to generate the next set of structures. For instance, from the additive manufacturing standpoint the build orientation, power source, laser focus/path, laser speed and time become some of the important information stored in the iteration process. As depicted in earlier Fig. 2, a progressively better population is obtained at the end of each iteration, and they are ranked according to a fitness function to ensure the best chromosomes are passed to the next population as shown in Eq. (3)

$$P(t) = P(t-1) \times I(t-1) \tag{3}$$

6 Case Study: Generate Design of a Chassis for a Drone

There are numerous project examples in the architecture, engineering and construction fields, implementing generative design empowered artificial intelligence algorithms as an innovative design instrument. Several competing finalized product goals are balanced in generativity design methodology. The generative design methodology can provide a varied design option for decision makers to reach required solutions in their studies. Artificial intelligent-based algorithm-driven generative design utilizes iteratively the design parameters to achieve the finalized optimal design output. To take a look at the generative design process integrated with hybrid additive subtractive manufacturing and to explore its capabilities, a case study which covers drone chassis design integrated with hybrid additive subtractive manufacturing is conducted. Drones are unmanned air vehicles (UAV) that can be manually operated by humans or can fly autonomously. It is clear that drones will play a significant role in the future of the establishment of smart cities since they can offer cost-efficient services in different smart city applications such as package delivery, traffic monitoring, policing, transportation of people, pollution control, firefighting, rescue operations and security purposes [64, 65].

Logistic drone chassis is selected as a case study in this chapter since logistic drone systems will offer many advantages in smart city applications. Furthermore, the logistic drone chassis application seems to be of interest to engineers and designers for varied air applications especially in smart cities. This section explores initially the drone chassis creating process with generative design systematically from scratch to final outcome design. Additionally, the integrated hybrid additive subtractive manufacturing process is also clarified in the manufacturing process of the preferred generative design solution. The main parameters to be chosen for the case study will give an idea of generative design solutions integrated with hybrid additive subtractive manufacturing for different smart city applications.

The preferred solid model which is created through the generative design rules and algorithms is processed via cloud-based Autodesk Fusion 360 software [66]. Apart from the generative design methodology, which is conducted for a specific engineering application, a hybrid additive subtractive manufacturing concept is included with proper hybrid manufacturing examples in the section. An optional starting geometry can be designed in the first step of the generative design methodology. The components with relevant geometries to be assigned and determining the dimensions. Generative design differentiates with topological optimization with the use of varied constraints while computing generative design algorithms. By entering the input geometries (starting shape, obstacle geometry, and preserve geometry), loads (forces and pressure), constraints, and objectives (target mass, maximized stiffness) into the algorithm, 100's of higher performing design options can be explored. Starting shape

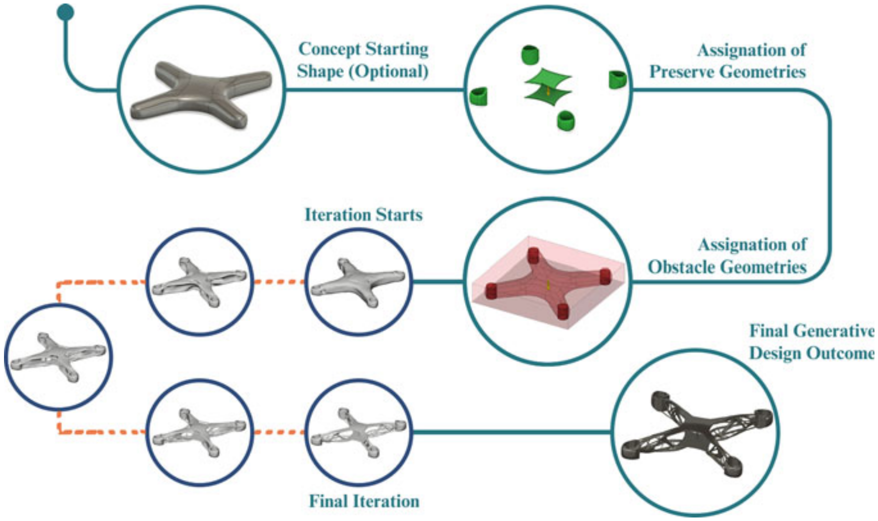

Fig. 8 The drone chassis creating workflow via generative design methodology

is an initial shape, close to a design envelope. Obstacle geometry is the part geometry that cannot be generativity created such as the interior channels whereas preserve geometry is the geometry that will be included in the final shape such as existing connections or interfaces within an assembly. In Fig. 8, the generative design case study workflow for drone chassis is shown.

In order to gain the full advantages of hybrid additive subtractive manufacturing, additive manufacturing related design constraints should be carefully specified during the generative design process. Two samples of scatter plot view of concept drone chassis outcomes in generative design workspace of Autodesk Fusion 360 software are shown in Fig. 9.

In the scatter plots, it is possible to predict how much the designs meet the constraints that are given as input to the generative design process. Minimum factor of safety and mass values were selected in this case study as the preferred selection criteria since the weight plays an important role in the design of drone chassis. However, additional criteria such as manufacturing cost and maximum stress can also be included into the model. Furthermore, the generative design algorithms can suggest varied design options for different materials. This feature is one of the main differences from the topology optimization that provides an optimized design for a specific material type. The designer can select a preferred design solution according to the established scatter plot.

Two different drone chassis design outcomes which are extracted from generative design are shown in Fig. 10. For these designs, additive manufacturing and 5-axis milling were selected as production methods. As a result, generative design solutions which are suitable for these specific methods were generated. If no manufacturing method is selected as a criterion, then the so-called unrestricted designs can be

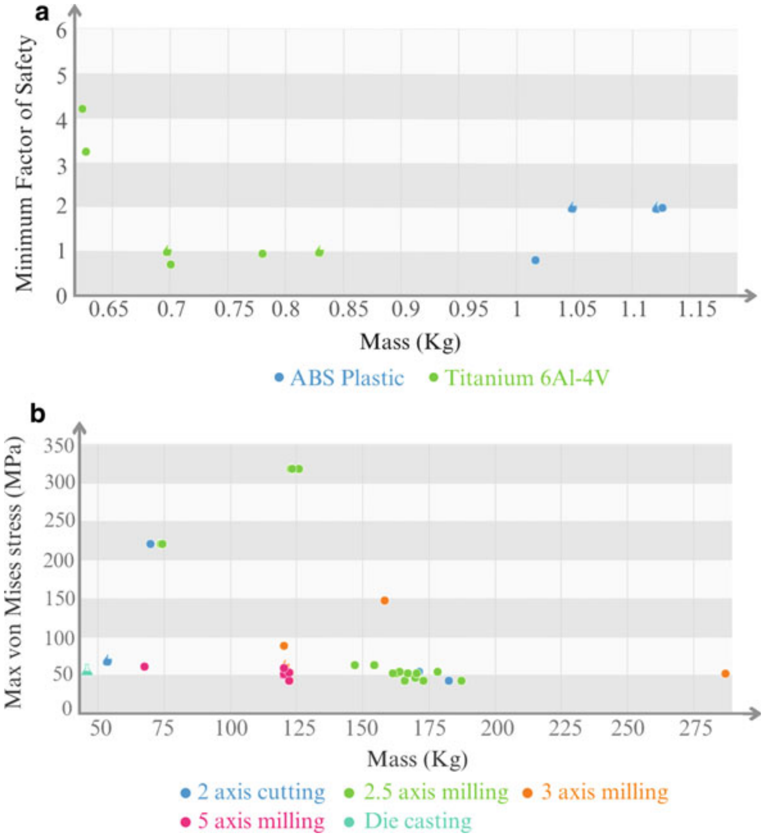

Fig. 9 **a** Scatter plot of concept drone chassis outcomes in generative design workspace of Fusion 360, **b** scatter plot view of front loader outcomes which designed according to different manufacturing methods for excavator

created. For the design proposed according to additive manufacturing, application of subtractive manufacturing methods would not always be possible, and the same result applies to the opposite case. This shows the need of considering hybrid additive subtractive manufacturing relative parameters during the generative design process. In order to give an idea on this concept, a design which combines both additive manufacturing and 5-axis milling is represented in Fig. 10.

In this case study, it was assumed that the four parts on the drone chassis where the propellers are mounted shown in Fig. 10 will be produced from a higher strength material. Therefore, using 5-axis milling for production and machining of these parts will be more suitable. In case a specific additive manufacturing method will be used for production, this should also be integrated into the generative design process. Now as the hybrid additive subtractive manufacturing parameters are also analyzed in generative design algorithms, the selected best design will directly be produced by hybrid additive subtractive manufacturing. As a result, the compatibility of the

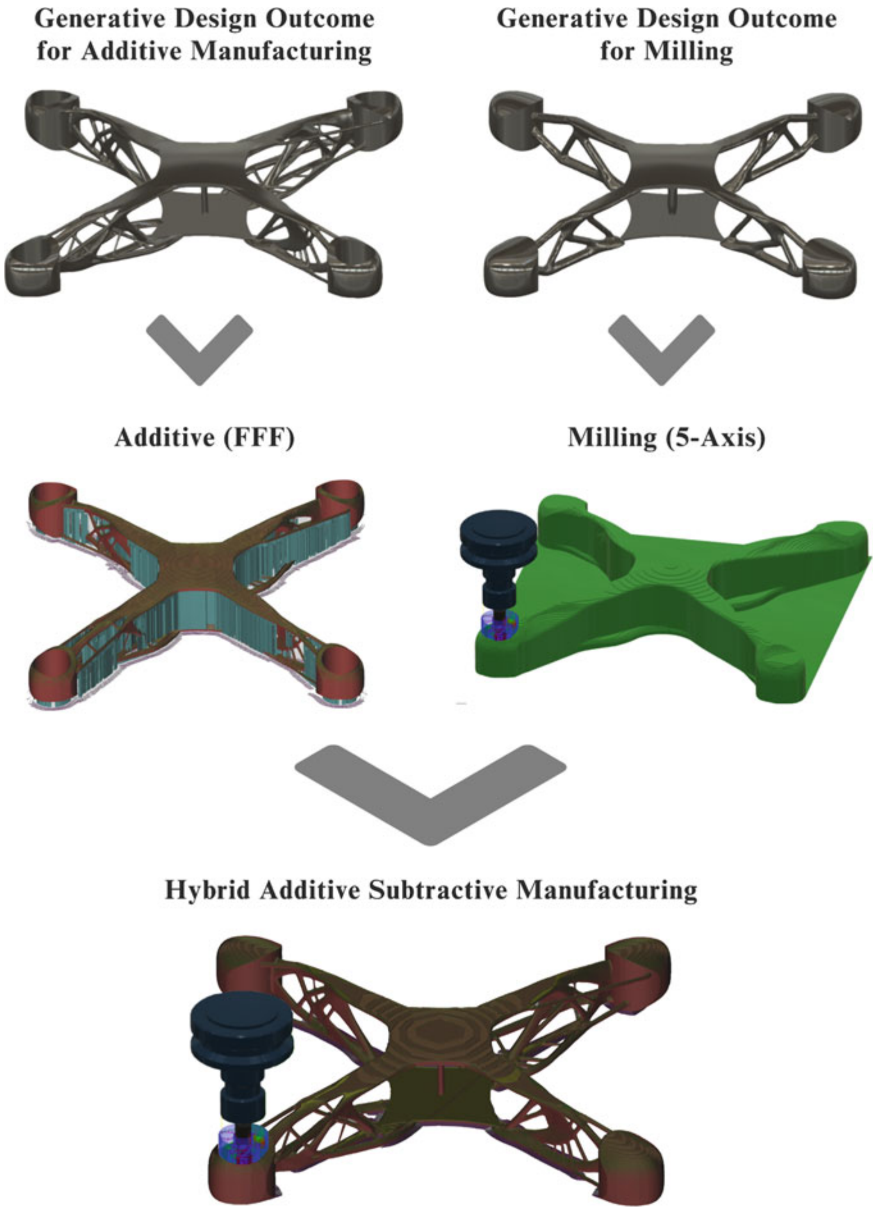

Fig. 10 An illustration showing two different final outputs for additive and milling methods created by generative design integrated with hybrid additive subtractive manufacturing

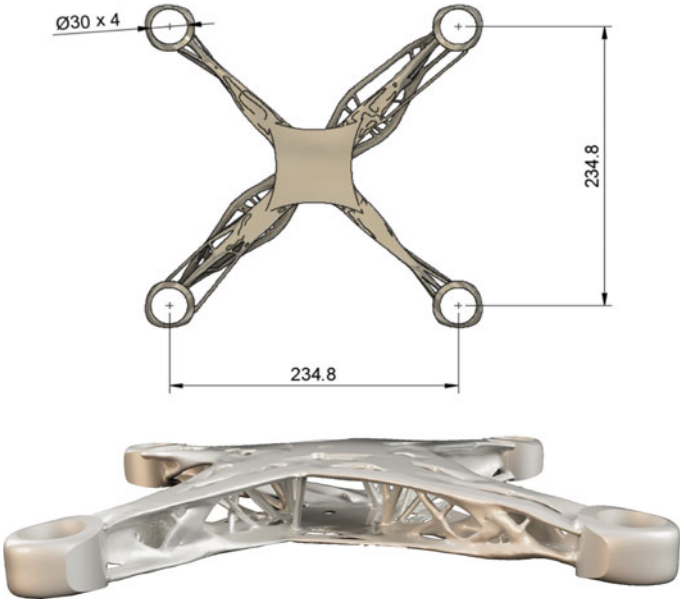

Fig. 11 Dimensions (in mm) of the finalized drone chassis as an end product

design to hybrid additive subtractive manufacturing is questioned within the design process. The selected outcome of the concept drone obtained by generative design is shown in Fig. 11.

7 Conclusion and Future Scope

Generative design is a systematic designing process through nature mimicking in an evolutionary manner. In recent years, nature has become a significant source of design inspiration for engineers, architects and designers. In generative design, many factors such as sustainability, energy efficiency, structural strength, materials selection, environment technologies can be taken into consideration while designing. Generative design offers several non-regular shaped design solutions for the decision makers. Engineers, architects and designers evaluate the potential design options and decide on the final design based on a wide perspective. Generative design reduces construction time and offers practical compromises for end goals. A software can provide many data-driven potential design options to meet the finalized goals with related constraints. With technological developments in additive manufacturing methods, a concept that integrates hybrid additive subtractive manufacturing with generative design has become important for the generation of print-ready digital designs. Hybrid additive subtractive manufacturing sensitive data-driven generative design approaches can provide an optimized product solution with structural stability and desired aesthetics. As a result, an optimized end product can be built by applying generative design integrated with hybrid additive subtractive manufacturing methodology.

The most significant technological innovation that can be provided by this concept is the integration of two vital processes with the data collected from the smart cities. In this concept, the dynamic up-to-date generative design options that are suitable for hybrid additive subtractive manufacturing can offer better solutions than the traditional design and manufacturing counterparts for the future smart cities. A cloud-based continuum generative design with integrated hybrid additive subtractive manufacturing concept can provide a unique digital manufacturing system which is accessible from any IoT device. Engineers, architects and designers can decide on the selection of the final designs via a continuum digital system that combines the generative design with hybrid additive subtractive manufacturing in varied industrial fields. The increased innovative flexibility of the production line accelerates generating novel state-of-the-art products. In addition, a digitally automated hybrid additive subtractive manufacturing system can reduce repetitive processing activities with related digital continuity. An online data collection system which is dedicated to the cloud-based continuum generative design with integrated hybrid additive subtractive manufacturing concept can provide potential design update opportunities according to updated data received online from smart city and previous designs. Thus, for the same application, updated design solutions can be obtained since increased data is collected from the smart cities and design itself. In addition to data-driven design update solutions, this will improve the design security and design sustainability in the cities of the future. As a result, the suggested concept will provide a design sustainability with the product lifetime perspective for smart cities. In addition, a combined data-driven design and manufacturing framework will facilitate the integration of the IoT-based design and manufacturing instruments to industry 4.0 with big data analytics. As a future work, all of the critical parameters that affect the hybrid additive subtractive manufacturing process should be parameterized by using data-driven machine learning algorithms. After that, these extracted parameters can be integrated into design software libraries for optimizing the hybrid additive subtractive manufacturing integrated generative design process for the smart cities of the future.

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