Enhancement of an electric drill body using design for additive manufacturing

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Abstract. Our research work involves the use of digital manufacturing tools to develop a novel design alternative to an existing application. An everyday electric drill machine has been considered and had its functionality enhanced by redesigning its body in accordance with the solutions aimed at mitigating a few shortfalls, which primarily involves its safety aspects and ease of use, while also not compromising on its extant operating capacity as well as retaining the ability to be wielded by professionals well-versed in handling the original machine. To that end, we deconstructed the CAD (Computer-Aided Design) model of a conventional drill, and attached an auxiliary (precision) grip through generative design - a superior designing experience that is powered by Alternative Intelligence - by using Autodesk Fusion 360 software. Then, it was converted to an STL file (Standard Tessellation Language), which is a competent file format for subjecting the design to the various pre-processing steps required for creating a physical model of it using additive manufacturing. Firstly, file repair and manipulation tasks were carried out through Autodesk Meshmixer and Netfabb, with the latter also doubling up as the implement used for carrying out the printability analysis, orientation optimization, construction of support structures, and finally, slicing. The finished model was of the dimensions of 165.3820 mm x 204.4808 mm x 76.2340 mm, which indicates that the design alterations did not produce a vastly different version of machine than the original one. However, the output would be considerably efficient since the overall weight is reduced, and the presence of auxiliary handle would bestow more control on the operator. This also renders the body of the electric drill a monolith, which would enable a simpler assembly operation during the manufacturing stage. The material of choice was Orgasol polyamide - a natural polyamide 12 powder possessing the physical and chemical properties suitable for this application. The specific additive manufacturing process to be used was determined to be Selective Laser Sintering, and a printer capable of performing the same was identified as Formlabs Fuse 1. The aforementioned printability analyses were carried out in accordance with these considerations and the model was found to be well in order for the same.
1. Introduction
The advent of 3D printing, or additive manufacturing, has opened up a world of possibilities for the designer [1]. Design for Additive Manufacturing (DFAM) principles and technologies are put to use in a multitude of applications, by way of providing solutions to alleviate problems and inconveniencies in extant configurations, owing to the constraints imposed by conventional designing and manufacturing processes [2]. The unique selling point of DFAM has been the ability to optimize models to a level of composition that is almost nearing perfection, in terms of reduction in mass, weight, material consumption, and increase in precision, ergonomic compliance, energy storage and transmission, wherever applicable. The method employed by additive manufacturing to construct objects customarily layer by layer, either by depositing material, or by fusing liquid or solid particles by heating them using various sources, started out as an option for designers seeking purely aesthetic or prototypical formulations [1]. Visual appearance is oftentimes an essential characteristic of a product. Rapid prototyping granted advantages of the possibilities to assess the component by touch and feel, and to work out the nature of the fit, if it were a part of an assembly, by virtue of resulting in a physical real-world entity. Also factoring in how rapid prototyping took no longer to be constructed that a computer simulation, the former proved to be a more impressive proposition than the latter. With time, this idea began to elicit growing degrees of acceptance, with it presently being on the brink of making its way into industrial production en masse [3].

One of the technologies that have taken centerstage by dint of DFAM for computer-aided conceptual design is Generative Design. It is a revolutionary software tool, powered by Autodesk, which employs sophisticated Artificial Intelligence (AI) algorithms to conduct an iterative design process [4]. The designer only needs to feed in the problem, or in other words, describe the component needed to be built by specifying the function it needs to serve in terms of the obstacle geometry around it, the safe geometry which must not be tampered with, and other load parameters which the part to be constructed needs to withstand. In addition, the user also needs to stipulate a choice of material and manufacturing method. The software then factors in all these criteria and provides a series of outcomes by iterating all possible solutions to the problem, each having unique properties or form, along with their specifications like Von Mises stress, the factor of safety, mass and volume occupied. All these would enable the user to evaluate and select an outcome that is the best fit for their intention.

An electric drill is a versatile tool that has the capacity to perform a variety of jobs based on the type of attachment provided to it. When equipped with a drill bit, it would perform drilling of holes, owing to its spinning tip [5]. Common problems associated with the drill are its high risk in operation, its propensity to accidents because of the high speed at which it operates and the excessive stress which it exerts on the user [6]. Another issue is the lack of control over the drilling process, except for highly experienced professionals. In this research, we have made use of DFAM principles and Generative Design to provide a redesigned, enhanced version of an electric drill, equipped with a secondary, precision grip that aims to render the drilling process safer and easier for the operator [7].

2. Methodology
The scope for improvement in the design of the common drilling machine is chiefly based on the extent of difficulty with which it is operated [8]. We started by seeking out areas where we could work on, in order to bring about an improvement in that regard, while also not compromising on the existing functionalities that it houses. We confined our study to the body enclosing the drill, since the organic brand of designing that generative design brings to the table would not be exceedingly pertinent to be applied in other parts of the drill assembly, such as chuck, drill-bit, bearings, motors and other electromechanical equipment. Another feature that generative design bestows on models is the capability to make them monolithic, which can be manufactured quite easily by additive manufacturing, while it is nearly impossible to do the same by conventional machining. A monolithic body also has numerous benefits such as doing away with the time spent on the assembly of the body in itself (however,
any difficulties that may arise during assembly of other parts to the body have been obviated with the provision of entry points at strategic locations where they can be inserted and placed), and also the absence of the erstwhile joints that had to hold the many pieces of the body together. Such an alteration would mean that the body housed less stress concentration regions and would show better strength overall, which leads to less propensity to damage in operation or as a consequence of fatigue or creep [9, 10]. As a further measure, a secondary (precision) grip was proposed to be appended to the body, which promotes better stability in operation and grants the operator more control over the drilling process since they could now use both hands and exert a greater portion of the upper body strength to direct the drill. This further amplifies safety by reducing the risk of accident owing to any freak movement made by the solitary arm of the operator, in response to not being able to hold out against the force of the device, due to drilling for longer hours or under similar situations of duress or any conditions that could possibly deny them from having full command of the drilling process.

For designing such a secondary grip, attaching it to the body and properly constructing by employing generative design, literature reviews were undertaken initially to identify ergonomic norms to be adhered to, and to obtain an understanding of the kind of loads the component would need to endure in operation, or in other words, the load conditions and constraints that needed to be fed to the AI-based algorithm [11]. Ergonomic standards published by the Canadian Centre for Occupational Health and Safety (CCOHS) required that the secondary grip had its diameter between 8-16 mm for achieving greater control and length over 100 mm for keeping the contact out of palm [12]. Also, the separation distance between the main grip and the auxiliary had to remain between 65-90 mm to grant maximum grip strength. Thus, such an implement was created in the Autodesk Fusion360 CAD workspace, and mounted onto the originally-designed assembly of traditional electric drill, at a position that fulfilled the norms, while being least intrusive to performance. At this juncture, the preparatory steps for generative design were in order [13]. The challenge here was to suitably qualify and quantify the load conditions imposed on the handle during operation. Based on data concluded from a study, the maximum possible force to be applied by a human hand, on a handle at the time of drilling was about 250 N including the factor of safety (blue arrow in Fig. 1) [14]. We experimented with the different qualifications available in Fusion360 to be given for the nature of the load. Out of the many studies we performed in that manner, the most successful outcomes belonged to the studies where we had considered it to be bearing stress (such a qualification would be tantamount to the way in which the hand applies a load on the grip). Furthermore, the mandatory condition of gravitational force also had to be applied onto the setup (yellow arrow in Figure 1).
Figure 2. The two versions of obstacles created (first and second images from left), out of which, the cylindrical-shaped obstacle (second image from left) proved to result in more appropriate generative design outcomes.

Another part of this preparatory stage is the demarcation of two types of geometry – obstacle and preserve [13]. The areas marked as obstacle geometry (red regions in Figure 2) would be interpreted by the software as the bounds for construction, while not including them as such in the final outcome. Two different creative ideas for the shape of the obstacle had been tested with in the different studies, since it is better to let the computer grant us more options in that way for scrutinization. Regions listed under preserve geometry (green regions in Figure 2) are understood to be untouched in the iterative process. In our setup, 26 parts had been selected to be included in the final form of the design. As mentioned earlier, the option to input the mode of manufacture was also exercised and it was given as “Additive”. Two choices of materials had been considered: Orgasol and Rilsan, by virtue of their properties favoring this particular application. Further sections of this paper would shed light on the plan for additive manufacturing. In total, 5 separate studies with various combinations of the aforementioned parameters had been devised, in order to learn how effective our designing ideologies were, and to seek out a winning combination. The crucial results of these studies are discussed further in detail.

3. Results
This section provides an insight into the various results obtained, firstly at the end of generative design, and later on, the additive manufacturing pre-processing and feasibility analysis procedures.

3.1. Generative Design Outcomes
The software generated 57 outcomes across all the studies, among which four iterations that best replicated the requisite geometry, with the most competitive properties had been picked out and displayed for a final round of sifting, along with their study and outcome numbers for identification in Table 1. Finally, the eighth outcome generated in the fifth study (Study 5/ Outcome 8) had been adjudged to be the best choice [15]. It was evident from the parameters shown, that this particular outcome possessed the least build volume, least mass, and least global displacement.
Table 1. A consolidation of the important parameters obtained from the most suitable outcomes that were provided by the software.

| Properties                  | Study 5/ Outcome 5 | Study 5/ Outcome 8 | Study 4/ Outcome 5 | Study 4/ Outcome 8 |
|-----------------------------|--------------------|--------------------|--------------------|--------------------|
| Status                      | Converged          | Converged          | Converged          | Converged          |
| Material                    | Rilsan Invent      | Orgasol Invent     | Rilsan Invent      | Orgasol Invent     |
|                            | Natural – PA 11    | Smooth – PA 12     | Natural – PA 11    | Smooth – PA 12     |
| Orientation                 | Y+ Additive        | Y+ Additive        | Y+ Additive        | Y+ Additive        |
| Manufacturing Method        | Additive           | Additive           | Additive           | Additive           |
| Visual Similarity           | Group 6            | Group 6            | Group 3            | Group 3            |
| Production Volume (pcs.)    | 2500               | 2500               | 2500               | 2500               |
| Volume (mm$^3$)             | 207,853.71         | 207,159.25         | 209,349.19         | 221,199.98         |
| Mass (kg)                   | 0.212              | 0.199              | 0.214              | 0.212              |
| Max von Mises stress (MPa)  | 21.5               | 23.5               | 21.5               | 23.5               |
| Factor of Safety limit      | 2                  | 2                  | 2                  | 2                  |
| Min factor of safety        | 2                  | 2                  | 2                  | 2                  |
| Max displacement global (mm)| 3.02               | 2.75               | 3.13               | 2.61               |

Therefore, the chosen outcome fits all required criteria and achieves successful integration of the auxiliary grip into the conventional drilling machine body, as demonstrated by it having adequate physical properties in order to be used for such an application. The next step was to make sure that the CAD model created was made to satisfy the requirements for additive manufacturing.

3.2. Pre-processing Steps for Additive Manufacturing

3.2.1. STL Conversion. The choice of outcome (S5-O8) had to be subjected to a number of operations using various specialized software made to refine a CAD rendering for the purpose of 3D printing, and further analysis before proceeding to send it to a suitable 3D printer for construction, which can be broadly termed as the pre-processing steps for additive manufacturing. The first of those is the conversion of the file from a native CAD format (.f3d here) to the STL file format, which is widely regarded as the de facto standard for additive manufacturing worldwide [16]. It reconstructs the CAD model into a three-dimensional mesh of triangles, which are represented by values depicting each of their unit normal and vertices according to Cartesian coordinates, and following the right-hand rule. This STL conversion is performed through Fusion360’s in-house feature, with the refinement value set at “medium” - in order to achieve a relatively faster rendering with the accuracy not taking a hit, - to find ourselves in possession of an STL file with 24849222 triangles. This file then had to be exported to Meshmixer for the next stage of refinement.

3.2.2. STL File Manipulation. The Autodesk Meshmixer workspace holds a wide variety of tools for working with meshes to bring them to a desired form and structure [17]. The organic nature of the generative design outcome selected meant that it could not be considered for production in its original form. The model had some regions of inexplicable, excess material deposit which called for removal since otherwise, the part would not perform as well as envisaged owing to stress concentration in
irregular, inconvenient areas, hamper the effective device usage, and also make it an unnecessarily difficult standard to follow in case of possible mass production in future [18]. Thus, the design was exported onto Meshmixer where various Sculpting and Optimization tools in conjunction with numerous Brushes were engaged to smoothen any triangles damaged in the mesh as a consequence of the aforementioned processing. At the end of this activity, the model was obtained in the form depicted in Figure 3.

![Figure 3](image)

**Figure 3.** This model was obtained at the end of STL file manipulation using Meshmixer.

3.2.3. **STL File Repair.** The STL file repair was done with the help of Autodesk Netfabb software to make the model watertight and rectify the packing errors. Every error that can come up in an STL file does so due to its fundamental concept of representing a smooth 3D surface using a high number of tessellated triangles. Ideally, the edges of these triangles line up perfectly to form an airtight surface and problems ensue when this is not the case. Netfabb provides an automatic AI-based holistic file repair feature and also grants its users the chance to exercise more control over the process either in a semi-automatic manner through pre-programmed support scripts, which are akin to algorithms that can be set to identify certain conditions in the model as errors, and perform specified alterations to rectify them accordingly, or by taking a manual approach where there are separate options to indicate different kinds of errors and solve them on a case-by-case basis [19]. Owing to the amount of processing being done on our model till this juncture, it would have been a fairly inefficient and ineffective endeavor to employ anything other than the automatic approach. Netfabb conducted its operations and delivered a corrected model, whose veracity had been cross-verified as part of the printability analysis.

3.2.4. **Printability Analysis.** Once the model had been converted into a perfect meshed body, devoid of any defects (Table 2), and in the desired final form of printable product, a few analyses were needed to be conducted in order to account for the printability of the body, and to formulate a plan for 3D printing. Printability has been determined by a standard analysis - that has reaffirmed that the part is watertight, - in company with computation of parameters such as wall thickness, upskin and downskin [20]. Firstly, properties of the model such as volume, surface area and position on the platform were determined by the standard analysis procedure, which also calculated the number of points, edges, shells and triangles in it. Also displayed are the quality and quantity of defective entities, based on which, a final result is shown as to whether the part is closed and ready for the following step of determining its orientation.
Table 2. Standard analysis results.

| Parameter                          | Result         | Parameter                        | Result |
|-----------------------------------|----------------|----------------------------------|--------|
| X - axis size on platform         | 155.22 mm      | Shells                           | 1      |
| Y - axis size on platform         | 210.96 mm      | Holes                            | 0      |
| Z - axis size on platform         | 76.21 mm       | Boundary Edges                   | 0      |
| Area occupied                     | 1066.1743 cm²  | Flipped Triangles                | 0      |
| Volume occupied                   | 205.3798 cm³   | Bad Edges                        | 0      |
| Edges                             | 583914         | Surface is closed                | Yes    |
| Triangles                         | 389276         | Surface is orientable            | Yes    |

Wall thickness is a property dictated by the material used for manufacturing, which here is Orgasol, a polyamide 12 powder that is adjudged to favour a minimum thickness of about 1 mm [21]. Therefore, the test was undertaken to ensure that the entire body, barring a minimum tolerable threshold, surpasses this stipulation, and was found to be so (Table 3).

Table 3. Wall thickness analysis results.

| Parameter                        | Result         |
|----------------------------------|----------------|
| Wall Thickness Threshold         | 1 mm           |
| Surface Threshold                | 5 %            |
| Area below Threshold             | 0 % / 16.9255 mm² |
| Wall Thickness Test passed       | Yes            |

The angles made by all surface areas of the body with the print-bed are measured, and among those, the areas having less amount of inclination (in relation with a certain threshold angle value) are picked out and termed as either “upskin”, or “downskin”, and are illuminated by the upskin/downskin analysis. Among these areas, the ones oriented downwards represent the upskin, and those oriented downwards are classified as downskin (Figure 5). The data from this analysis may prove to be crucial in some production methods in which changing the orientation to bring about a minimization in upskin and downskin regions proves to be prudent because of the difference in quality exhibited while building them [19].

Figure 4. Downskin (Inverted view) (left) and Upskin (right)

3.2.5. Orientation Optimization. Orientation optimization is the stage where the orientation of the part with relation to the print bed is adjusted to maximize or minimize one or more manufacturing considerations. It has implications on how the mechanical properties of the finished product would turn out, since each orientation changes the way in which material is distributed across the platform [22]. Netfabb runs a program that devises a number of different possible orientations for us to choose
one from, once we input our preferences, much akin to how one most pertinent outcome is selected out of many at the end of generative design (Table 4).

Table 4. Input given for generating possible orientation outcomes.

| Parameter                        | Specification |
|----------------------------------|---------------|
| Critical Angle                   | 45°           |
| Vertical Distance to Platform    | 0 mm          |
| Smallest Rotation between Orientations | 45°       |

Among the nine iterated models prepared according to the specified conditions, and displayed along with five of their properties that would have a significant bearing on manufacturing, Outcome 3 has been selected, by virtue of it possessing the least outbox volume, the best center of gravity position, and the third-least support volume, all of which mean that it would result in the most stable printing process (Table 5).

Table 5. The aforementioned outcomes with properties for orientation.

| Model | Supported Area (cm²) | Support Volume (cm³) | Outbox Volume (cm³) | Height (mm) | Centre of gravity height (mm) |
|-------|----------------------|----------------------|---------------------|-------------|-------------------------------|
| 1     | 134.990              | 440.638              | 2495.397            | 155.2       | 72.0                          |
| 2     | 134.139              | 451.402              | 2605.428            | 160.6       | 75.8                          |
| 3     | 251.187              | 622.288              | 2495.395            | 76.2        | 38.0                          |
| 4     | 253.010              | 632.587              | 2495.395            | 76.2        | 38.2                          |
| 6     | 251.209              | 681.569              | 2495.396            | 155.2       | 83.2                          |
| 7     | 134.239              | 656.872              | 2578.040            | 76.2        | 38.1                          |
| 8     | 123.646              | 358.848              | 3533.392            | 134.1       | 56.9                          |
| 9     | 120.582              | 505.813              | 3637.287            | 135.4       | 77.5                          |

The size of the figure is measured in centimeters and inches. Please prepare your figures at the size within 17 cm (6.70 in) in width and 20 cm (7.87 in) in height. Figures should be in the original scale, with no stretch or distortion.

3.2.6. **Support Structure Generation.** The next measure is to proceed toward building support structures for the selected orientation. The pre-loaded support scripts available in Netfabb were utilized for a fully-automated support generation process, by selecting the one titled ‘SLM’ (Selective Laser Melting), which is the most appropriate option for our desired process, Selective Laser Sintering (SLS). The supports were directed to consist of polylines, which are fence-like structures that are easier to break off than solid volumes and show an economy in material consumption. When utilized to support an area, they are arranged in parallel, and hence the additional specification of “Area with polyline support” was given (Figure 6). The critical angle was kept at 45°, which meant that any portion of the body that was oriented at an angle greater than 45° would be endowed with supports. This is being done to obviate certain undesirable events that may transpire during the printing process, such as deformation of part, detachment of peripheral features from the main body, and non-adhesion to the print-bed. The minimal area is the support structure’s minimum thickness and is kept as 0.10 mm, keeping in mind the precision of the 3D printer Formlabs Fuse 1 [23, 24], which is capable of SLS, and aimed to be printed by which, is our model being pre-processed.
3.2.7. Slicing. Slicing is the exercise where the model is transformed into a code that can be read and executed by the printer [25]. The height of the model is divided by the layer height of the printer, and a number of “slices” are obtained which contain the instructions for 3D printing including, but not restricted to the two-dimensional tool path and speed, are stored in a CSV file which is essentially the mantra which the printer obeys while moving in the third-dimension to wherever heat needs to be applied by way of solidifying the material, for each layer of the structure (In Figure 7, the path for layer 6 has been shown, as an example). This is necessary because it helps the printer and the user to be aware of the kind of result to be expected from each layer beforehand, and prepare accordingly, which is especially useful when printing structures that contain overhangs [26]. At the end of slicing, Netfabb provides a simulation of the tool path as each layer is created. Depending on the complexity of the model, performing some modifications at the slice level, rather than at the mesh level, can be significantly faster due to the simpler nature of the dataset [19].

4. Plan for Additive Manufacturing
As mentioned earlier, the design is to be constructed using Orgasol powder, which has uniform shape and narrow particle size distribution [27]. Polyamide 12 is a thermoplastic polymer that showcases high resistance to chemical action and UV rays, low water re-uptake and low density. Its features include excellent part detailing, maximum reuse of powder not used during printing, smooth finish resembling
that of injection-molded parts, which obviate the need for post-treatment. The printer to be used belongs to the acclaimed American 3D printing technology developer, Formlabs [23]. This benchtop model advertises efficient powder recycling and recovery, helping to cut costs and time. The build volume on this model is 165 mm x 165 mm x 300 mm. According to Formlabs, the printer displays a live stream of the print bed, enabling us to watch each new layer take shape. Our model, which is in dimensions of 155.22 mm x 210.96 mm x 76.21 mm (excluding support structures) is aligned with respect to its center of gravity and is printed. Post-processing involves getting rid of support materials at a cleaning station.

5. Conclusion
The 3D printed model can be relied on to render the electric drill safer, more stable, and easier to operate - a claim substantiated by the data and conclusions provided in the research article - as per the objective that we started out this research with. Having said that, further improvements in the existing design, as well as the proposed new design also find scope aplenty. Our approach took into consideration only the body while having other components such as the drilling mechanism, the drill bit in itself, as well as the motor and the switch mechanism produced separately as per the extant designs, and attached at appropriate regions in the body. The drilling mechanism can be reviewed, with measures to improve its efficiency worked on, or even a new mechanism altogether could be drafted in, to further proceed along the direction of making the drilling experience better overall. Weight reductions could be performed by improving the choice of material for the electrical components and the drill bit and chuck unit, where traditionally metals have been used. Throughout the course of this study, a multitude of tools and technologies have been employed, which has made the journey of a product, right from the stage of its conceptualization right up to the performance of a simulation that depicted the actual process of manufacturing it, guided by a number of meticulous analyses along the way, one that is characterized by efficiency, effectiveness, and most of all, ease of performance.

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