Sustainable Frugal Design Using 3D Printing

Ian Gibson and Abhijeet Shukla

Abstract This chapter describes and discusses achieving sustainable solutions through the fusion of 3D printing with frugal approaches in design and engineering. Sustainability has various definitions, however. According to the widely accepted Bruntland Report (World Commission on Environment and Development in Our common future. Oxford University Press, Oxford, p. 27, 1987) [1] for the World Commission on Environment and Development (1992), sustainability can be defined as 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. We can use this definition when we are dealing with product design to ensure the design functions correctly without causing a severe impact on available resources. For the chapter we consider sustainability as obtaining viable and tangible solutions for a given design problem which are environmentally friendly and economically advantageous for end users and society. 3D printing (3DP) is often regarded as a 'disruptive' technology that has forced many to rethink how we design and make things and how to turn this into new business models. It is also often considered as a 'liberating' technology that is easier to use, enabling us to transfer ideas generated in a digital format into physical forms with minimal fuss and cost. This chapter explores the product design and development process in relation to frugal and sustainable concepts and how 3D printing and related technologies can influence them.

Keywords Sustainable frugal design · 3D printing · Energy · Material utilization · Tool design

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1 Introduction

We start by analysing design in terms of the resources used during the process and in relation to the designs generated. Resources come in a variety of forms, but probably the most important ones used in design are manpower, energy, materials, and technology.

Manpower can involve the designers themselves, but also support staff, particularly in relation to the building of prototypes. It is generally measured in terms of time committed to the design process and there have been many attempts to optimise, automate, and generally speed up this process.

Excessive use of *Energy* is not usually an issue during the design process as we are often dealing with small numbers of products being made during this time. However, energy does become a focus for designers when they are considering the product's consumption during use as well as the energy required during manufacture.

Materials can be considered in a similar way to energy. The product design and prototyping process can be quite wasteful in terms of materials use because it is often necessary to build something in order to evaluate functionality. This would then allow the product to develop and therefore the material used would often be discarded. However, as mentioned above, we are dealing with small numbers and greater efficiencies can be had in downstream manufacturing stages.

The use of computer *technology* has revolutionised the design process. Many designs can be evaluated to a much greater extent as software models in some form of simulation. Although technology is primarily aimed at increasing efficiency, it can also reduce consumption of time, energy, and materials. Furthermore, there are downstream impacts where manufacturing technology can make better use of the digital information generated during this design process.

When considering frugal approaches to design we must understand it from both the product and process perspectives. The above-mentioned process issues relate mostly to the design process. A product perspective can be most easily understood through case examples. With increasing population and depleting natural resources, it is important to educate our designers on the important role they play in ensuring a more sustainable future. Designers must be frugal in the way they design and the products they design. Effective use of technology is part of this education.

2 Categorisation of Frugal Design

When considering frugal design, it is worth noting that there may be different approaches connected to the type of design. For example, we may like to look at frugal design of:

(a) Medical products
(b) Social innovations

(c) Business innovations
(d) Approaches in education and learning
(e) Aerospace technology
(f) Products and processes with environmental benefit
(g) Consumer products.

Medical products must have value to treat health issues or to maintain a good standard of health and this must be considered a priority during the design process. Poorly conceived or executed designs could potentially cause more harm than good. However, we can consider frugality at many levels in the development of products. The most obvious consideration would be to look at products that have been generated using a traditional approach and then redesigned to suit a poorer social group or a larger market to suit social and business requirements. Conventional approaches generally require large investment and development programmes that ensure safety and correct certification. Large companies don't normally consider sustainability during this process, at least not for new product innovations. However, it is worthwhile considering, even for complex aerospace applications where frugal approaches can result in significant operational savings, such as fuel costs. There is therefore significant value to incorporate frugality and sustainable thinking into grass-roots education so that all consumers may be able to benefit.

As part of an experiment in frugal design thinking, we can consider how a technology such as 3D printing can have influence related to the above categories. We revisit these topics once we explain a little more clearly what 3DP actually is to see how we can use it to make a more sustainable world.

3 3D Printing

3D printing (3DP) is the popular name for what is technically termed additive manufacturing and what has also been referred to as freeform fabrication, rapid prototyping, and layer-based manufacturing [2]. 3DP is generally compared with traditional carving and machining-based fabrication methods where material is removed (in a subtractive manner) to reveal the form of the final part. Instead, 3DP requires the addition of material, usually in a layerwise manner, to build up the final part. If the layers are sufficiently thin, then they can be considered as finite-thickness 2D cross-sections. This simplification of a complex 3D problem into a series of simpler 2D problems enables the process to be driven easily from computer-generated models. With the proliferation of 3D models and the ease in which they can be made, 3DP has proven to be a popular method of conversion from virtual to physical form. Further to this, 3DP printing machines have come dramatically down in price, making them affordable to individual users for their own recreational purposes.

The process for 3DP starts with a 3D digital geometric model. This model is usually processed within computer-aided design (CAD) software, but it is increasingly common for the source of this 3D model to come from medical scanning data or from 3D scanning technology. Such datasets allow the models to be customised to suit an individual or a specific location.

The real benefit of 3DP is that the process of achieving a real physical part is short, straightforward, and independent of the part geometry that is to be created. Figure 1 shows a typical process chain. Once the geometry has been specified by the user, the normal practice is to convert the file data into a generic form called an STL file. This file is a 3D surface model that can be easily used by the 3DP process to generate slice data. At this point, the machine may require some material or process-specific information such as slice thickness, build temperature, and the like. Default parameters can also be used here. Some processes require the generation of a supporting structure to be created to hold the part in place during the build. These supports would need to be removed once this build is complete.

The fact that parts are built using layers of material implies that the final part is an approximation of the intended geometry that is defined by the thickness of the layers. For certain applications, this approximation may be acceptable without further action. However, many applications would require the resulting parts to be post processed in order to achieve a smoother surface. Surface coatings may also be required to provide a desired appearance that cannot be achieved inside the 3DP machines. It is, however, quite easy to see that moving from art (computer model)

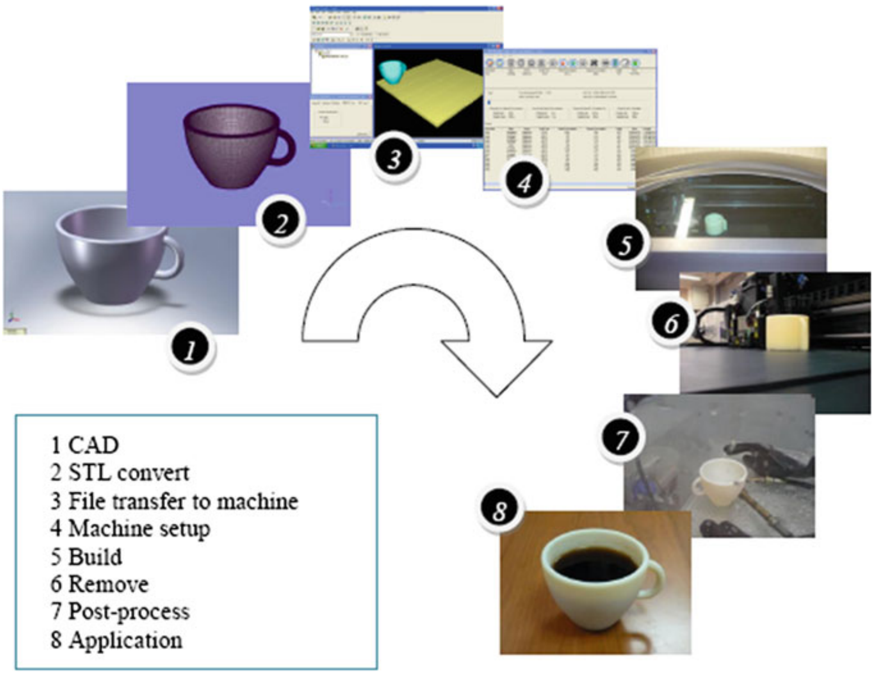

Fig. 1 The generalised process of 3D printing (reproduced from [2])

to part (physical model) is a systematic, largely automated, and straightforward process.

Applications can often be categorised according to the generic requirements from some of the early adopting industries:

Automotive industries have used 3DP primarily in the product development process. Here, designers are looking to create prototypes that will allow them to learn about how the final parts will behave in order to achieve a rapid time to market.

Aerospace industries use the technology to achieve final parts that have complex geometries. As previously mentioned, CAD modelling can produce surface geometry that can be difficult to fabricate using conventional means. For example, 3DP can create parts with features internal to the structure.

Medical industries are looking to create devices that fit to the unique form of an individual patient in a quick and affordable manner. By importing medical scan data, it is possible for 3DP to fabricate such geometries.

It is however becoming apparent that there is a fourth class of user. This generic class can be termed *innovators* who are using 3DP not only to develop novel geometric structures but also new business models. Media also refer to this group as 'makers' or 'disruptors' and it is clear that although 3DP is a key component in much of what they do, they also take advantage of other forms of simple-to-use, versatile technologies and combine them to create new and novel solutions. This integration of technologies is happening because they have achieved a stage of maturity where they are easy to use, fairly reliable, and affordable. These technologies range from computer- and mobile-based systems, through laser cutting/etching, to graphics and 3D scanning technology. We all know that mobile smartphones have onboard technology that can detect position, orientation, light levels, temperature, and other environmental conditions. Different application developers can use the same device to perform a variety of functions. This 'technology convergence' can also be used by designers to create 'frugal' solutions by adding a small amount of high-tech to low-tech systems to provide innovative solutions to everyday problems.

4 Frugal Design and Engineering

Frugality in design and engineering can be understood as the approach towards a desired target by using minimal available resources and eliminating inefficient factors without compromising the key features (as shown in Fig. 2). The concept of frugality may be traced from ancient India where in Sanskrit, the term *Yukti* is used for the innovative idea of providing a swift, unconventional, and alternative approach of solving a problem which could serve the purpose. The equivalent English term is known as 'frugality'. The concept of frugality is famously known and discussed as frugal innovation, Gandhian engineering, and Asian innovation. It is important to note the Asian roots to these approaches as we typically understand

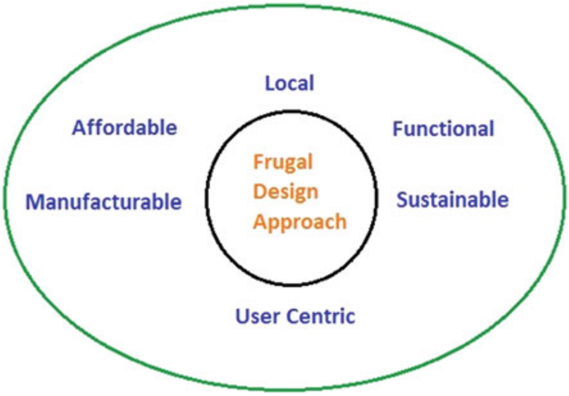

Fig. 2 Key features of frugal design approach

Asia to be a blend of high and low technology, illustrated by large wealth gaps and a significant population of very poor people combined with a wealthy infrastructure.

What makes the frugal approach more popular is the phenomenon of design to extreme affordability. Frugal design and engineering provides improvised disingenuous solutions combined with innovative 'smart' thinking. It can be understood as a philosophy of acting in a selfless, compassionate, but unconventional manner to create a better world for all, not just for a few. Simplicity of the frugal solution is one of the most sought-after criteria for solution selection; however, it is not necessary for any frugal approach to be simple.

Identifying the exact need is one of the important aspects of a frugal design approach. In the frugal approach a necessary/desirable output must be differentiated in smaller parts of achievable targets in a procedural format. Exact definition of need helps the designer to ideate in an efficient way and accurate achievable target differentiation helps in selecting the right approach. Frugal approach in design and engineering can be understood and practiced in the following areas.

- **Frugal Approach for Material Utilisation**
  This approach enables designers to use variations in material quantity and quality as per availability and requirement. The identified requirements shall be matched with available resources to perform. Let us discuss the case of 'adaptable baby carrier design (ABCD)' for developing countries. This example comes from a project that was part of a Design Programme held at IIT Kanpur as a course project for 'Special Studies in Design'. The objective of the project was to design and fabricate a low-cost baby carrier for developing countries which can be adapted by users much more easily than conventionally available products on the market. User survey and market research were performed by the team to validate and identify any problems other than those specified in the design brief. Cost and adaptability of the product are interrelated and linked by the material requirements for the product. The materials used in the existing products were costly and designs were intuitively not adaptable to a wide range

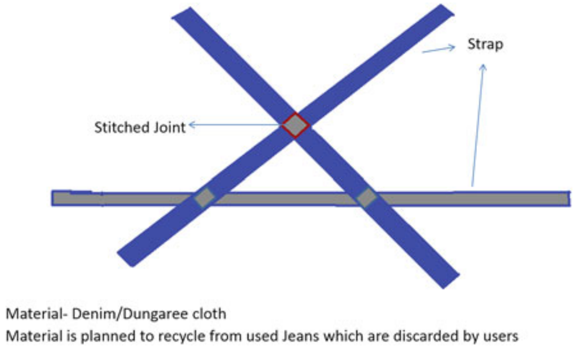

Fig. 3 Design of frugal baby carrier

of users (parents/baby holder). However, the ergonomics and baby postures provided by the existing products were well researched and validated by the companies providing the solution. To achieve adaptability in the new design solution and also cost reduction through utilisation of material, a concept was developed fitting the context of frugal approach in material utilisation.

In Concept 1 shown in Fig. 3 denim fabric strips from used jeans and denim suits were planned to upcycle and stitched together to form a baby carrier which can be tied at the back or in front of the user to carry the baby. Figure 4 shows a volunteer using the paper-made prototype to carry a dummy baby at his back. The frugal approach in selection of material and utilisation for the baby carrier lowered the cost of the product by up to 80 % compared to the market price of conventional baby carrier products. The frugal approach in this case has provided a sustainable solution for used and discarded fabric to re-enter the market and extend the utilisation period against a favourable cost of production.

- **Frugal Approach for Tool Design**

  Available materials can often be reformed and utilised as tools for specific purposes. Shape, size, material properties, and strength of material can be

Fig. 4 Mockup of frugal baby carrier [3]

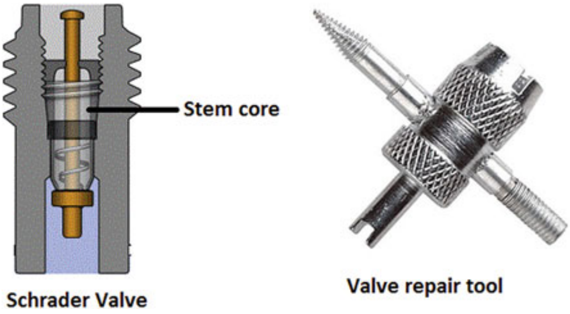

Fig. 5 Typical removal tool for Schrader valve repair

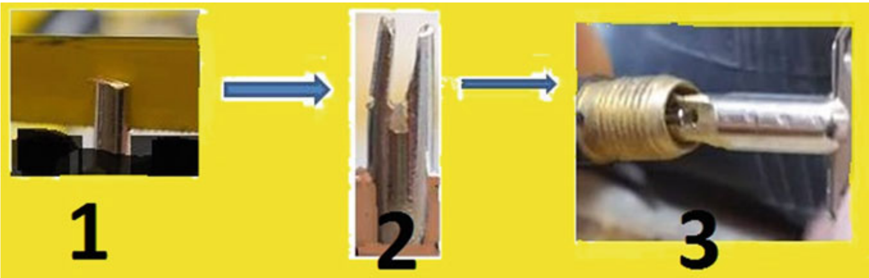

Fig. 6 Valve stem core opener

considered as parameters for identifying assets that may be utilised as such tools. There may also be some changes required for the fitting of selected objects to perform the tooling tasks; these changes can be permanent as well as temporary in nature depending on the task and physical properties of the material. Let us discuss the frugal approach for a tool design case in a design problem of cleaning a Schrader valve usually found in bike and car tyre tubes. To open the poppet assembly of the valve, a special tool is used as shown in Fig. 5.

But it is not necessary for every person, designer, engineer, and maker to have all the tools available every time in his or her workshop. Buying the tool can be an option but a tool can also be frugally designed by simply looking into available resources and finding something close to the requirement and then reshaping it to use as a tool to solve the purpose. As shown in Fig. 6 a simple metallic rod is selected to be reformed as a valve stem core opener. It requires the simple process of cutting and grinding to be transformed into the required tool.

- **Frugal Approach in Methods and Processes**

  In this approach a product, process, method, or system is identified and utilised to perform for desired process parameters for which the chosen system, product, process, and/or method is not designed. It can be achieved by merging and/or eliminating subsystems from other systems or the host. The process or method desired to be achieved should be economical.

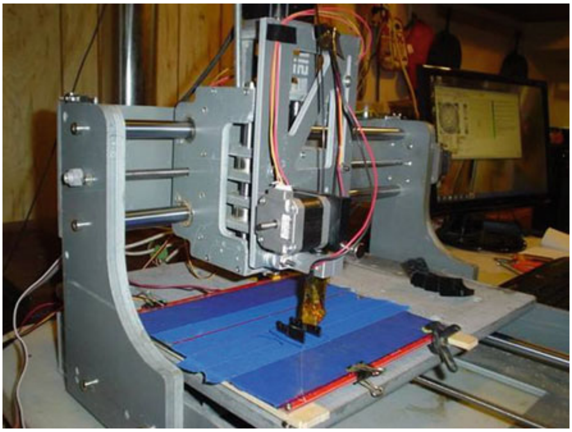

Fig. 7 CNC machine to 3D printer [4]

Conversion of three-axis CNC machines to a 3D printer is a good example of this approach. The CNC machine is a subtractive manufacturing unit and is totally different from the method and process of additive manufacturing; however, CNC shares a common physical three-axis mechanism for moving and positioning the tool from one point to another. As shown in Fig. 7, an FDM (fused deposition modelling) extruder is placed at the tool post of the CNC machine and STL to G-code converting software is used to get the modified code for 3D printing using CNC. The output from this setup should not be compared to the 3D printed part from a professional 3D printer. But this setup surely solves the purpose on a rough scale.

- **Frugal Approach in Application**
  Exploration of the product or process for in-genuine application is attempted in this approach. A computer-controlled two- or three-axis mechanism as shown in Fig. 8 can be made using CD drives of old computers. These mechanisms can be further used as plotter, CNC, and 3D printer. For old CD drives the application

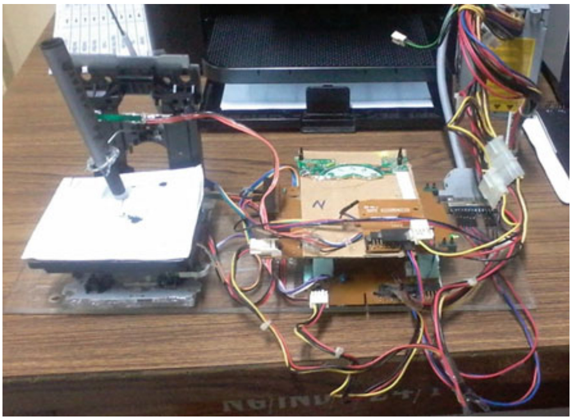

Fig. 8 Three-axis mechanism made using old CD drive parts

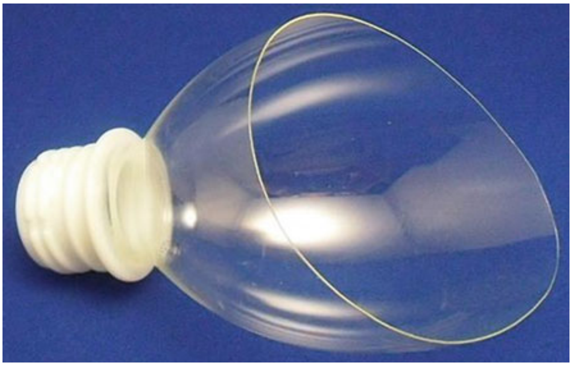

Fig. 9 Water bottle as funnel [5]

derived in this example is in-genuine all the way from design to application, as the designer of these CD drives did not design them to be used as a plotter or 3D printer.

- **Frugal Approach in Forms**
  Effective physical form according to requirements is generated in this approach. The form and shape of any other product can also be utilised in the approach to solve the purpose. Figure 9 shows a plastic water bottle can be utilised as a funnel by cutting it into the appropriate shape.
  A given or identified problem can be analysed for different parameters described above in the subheadings and then utilised for the concept generation for the solution of the problem. The whole process of frugal design can be understood by the flowchart representation in Fig. 10.

5 Frugal 3D Printing

As previously mentioned, 3D printing is often associated with innovative or disruptive business models. Such business models can include attention to frugal principles. The following are examples of how frugal approaches can be enabled by the use of 3D printing.

Component minimisation can be associated within frugal approaches. A product that has fewer components will generally be easier to assemble and maintain. The downside is that the components may be more difficult to manufacture. Drawing on the principle of ‘complexity for free’, 3DP may be able to overcome that obstacle. The example illustrated in Fig. 11 shows an air duct designed for an aircraft. Inasmuch as the duct has multiple channels and changes in direction, it is not possible to fabricate this easily as a single piece and the original solution required a number of components assembled together. Using a 3DP process that utilises an aerospace-grade material, it is possible to construct the entire duct, including mounting and connecting features, as a single piece. This is an excellent example to

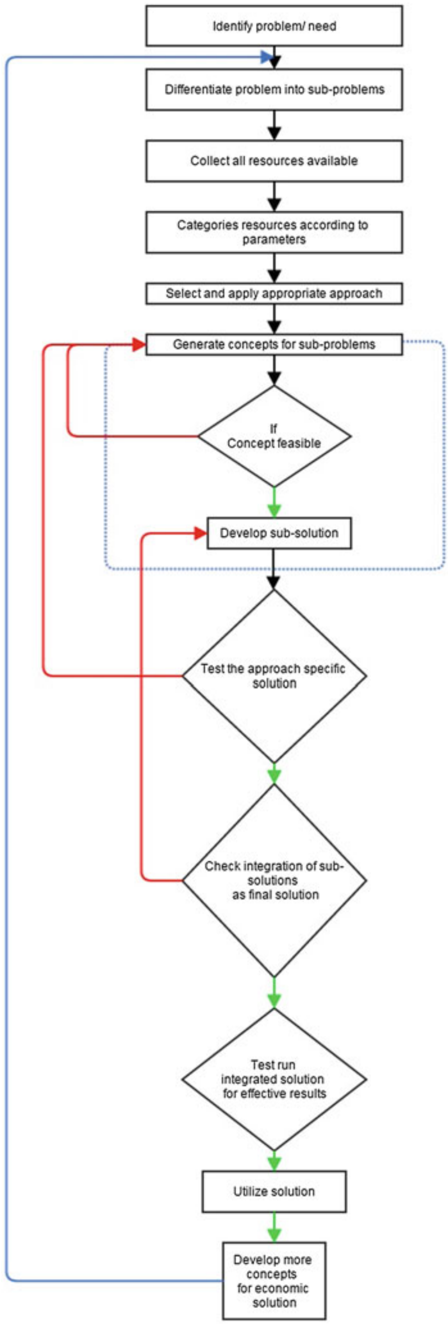

Fig. 10 Flowchart for a frugal design process: *green* flow lines are positive responses, *red* flow lines are negative responses, and *blue* flow lines show loop

Fig. 11 Ducting redesign using 3DP [6]

illustrate that 3DP can provide a frugal solution to complex, high-technology products as well as the more commonly-associated developing world issues. Note that a number of military organisations are using this approach to maintain their vehicles, thus proving that the quality and standard of such parts can meet stringent requirements in a range of existing applications.

Extending the previous concept further, it is possible to utilise 3DP to reduce inventory. This can be particularly relevant to spare-part storage but is also applicable to the manufacture of new parts. If it has been identified that 3DP can be used either to fabricate a new component or to replace an existing component, then it is possible to keep the inventory as a set of digital files. Immediately prior to use, we can initiate fabrication using 3DP to produce the required part. The data files will include part geometry, but may also contain information concerning the materials to be used, the required 3DP machine and build parameters, and other relevant supply-chain information.

Although aircraft and similar products have generic designs, there are often specific modifications that may make them unique. These modifications are referred to as *customisations* that adapt the base technology to suit a particular purpose or in response to the owner's or user's tastes. Manufacture of custom elements requires careful attention to detail and the site location of components. Design, planning, and tooling for these components can often be cost prohibitive. Noncustomised parts may fit the purpose to an extent but may often result in a suboptimal solution. Nowhere is this most evident than in the design and manufacture of medical devices. An excellent example where value is added through the use of 3DP to provide a higher performing result is in the design of in-the-ear hearing aids (Fig. 12). The casing of the hearing aid is taken from a digitised impression of a specific patient. This is then combined with more generic electronics and power to provide a more comfortable solution. This is now rapidly becoming the standard approach to hearing aid production, which also takes advantage of the complexity for free concept and the minimal inventory to provide a frugal solution.

To show that this approach of using 3DP to provide medical solutions can also extend into poor and deprived communities, the Robohand design provides an excellent illustration [8]. There can be numerous reasons why people can lose a hand. Sometimes, in isolated regions, it may be considered necessary or easier to

Fig. 12 Customised in-the-ear hearing aids made using 3DP [7]

amputate rather than save the hand. The Robohand device is one of a number of designs that have been developed to use low-cost 3DP to provide prosthetic solutions in this context (Fig. 13). The device can be modified easily to suit the size of the user and the extent of the injury and the components can then be scaled for building using 3DP. Furthermore, the design has a simple mechanism that uses cables and springs to open and close the prosthetic hand as the arm bends, thus providing a small element of dexterity. This design can therefore provide a significant additional value to the alternative, noncustomised, nonarticulated, strap-on systems. Many of these hands have been built and distributed through charitable and other sources. Examples have also been built for users in developed countries. It is worthwhile noting that many of these have no medical certification and have been built and (generally) very well accepted by the users and their communities because they are solutions that can be easily afforded.

Fig. 13 Robohand [8]

The Robohand and other low-cost solutions would not have come about if it had not been for a significant shift in the use and development in 3DP technology. In the mid to late 2000s, a number of key 3DP patents lapsed, particularly in relation to fused deposition modelling technology [ref Stratasys]. This allowed others to use this technology and create versions of FDM machines and sell them at much reduced prices. Many of these companies made use of an open-source version of the FDM technology called RepRap [9], an example of which can be seen in Fig. 14. By making this technology more affordable, the number of users has increased by a huge amount, vastly increasing the range of applications and allowing exploration into many new areas including food printing, bioprinting, and direct manufacture of low-cost, customised consumer goods.

Perhaps one of the most ambitious attempts to use 3DP to solve sustainability problems is in the automotive sector. An electric two-seater vehicle has been built, largely using a composite-material FDM-style printer. Shown originally as an experiment to be able to print a car in just two days, Local Motors has now launched the LM3D car shown in Fig. 15. Most of the chassis and body are made as a single piece using a carbon composite 3DP process. Although it still requires a lot of hand finishing and fitting out with motor, controls, and the like, this car can aim to replace the demand for low-cost short-range vehicles. Perhaps it is debatable whether it is a frugal solution, but one can see that the significant reduction in

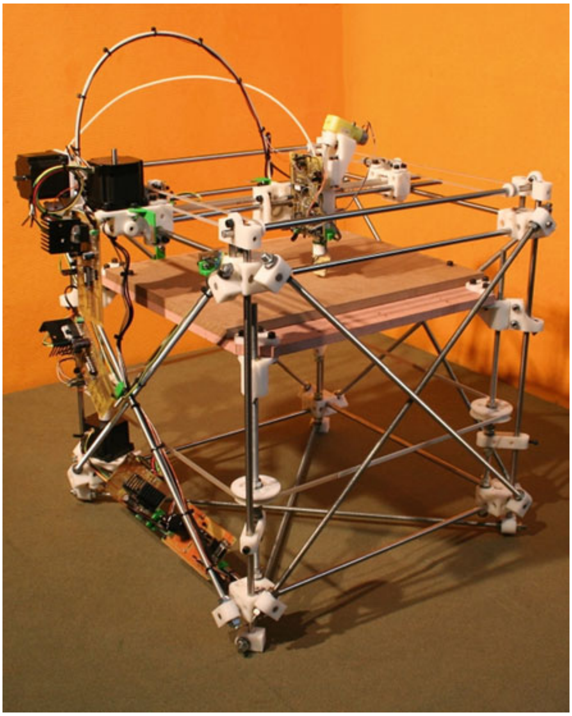

Fig. 14 The RepRap Darwin machine [9]

Fig. 15 LM3D car made using 3DP [10]

tooling, inventory, time, and manpower required to build it does indeed make it a potential contender. Regardless, it is an excellent illustration as to how far 3DP has come and how far it can go.

General issues that are worth mentioning at this stage include the ability for 3DP to make use of recycled material. Aside from the support material used to maintain the build geometry, 3DP only uses the material required to build the part. Comparing that with subtractive processes already makes it a material-efficient process. One must appreciate, however, that the material must generally be prepared according to a specific feedstock requirement and supplied in powder, filament, or cartridge form. The relatively low number of machines in circulation (when compared with CNC machines, e.g.) does mean that material is quite expensive. However, the low-cost FDM machines have driven material prices down and one can expect that to continue and eventually to cause this to happen for all 3DP technologies. It has been known for some users to produce their own feedstock, even using recycled materials. The problem with recycling polymers is that the mechanical properties are likely to degrade. Furthermore, it is not always clear what the original polymers were before recycling and one is very likely to be blending it with other materials with uncertain results. The common method to overcoming some of these problems is to use a filler material, such as chalk or rubber particles (taken from recycled car tyres) to create a more uniform result that may at least provide a reasonable compressive strength for nonload critical applications.

Another debatable point is energy utilisation. Inventory (and thus waste) is significantly reduced by using 3DP to create parts to order. If the 3DP machines are placed geographically close to the final market, then there would be significant reductions in shipping and the associated carbon footprint. However, manufacturing parts by adding material in layers is a painstakingly slow process when compared with volume manufacturing, particularly where polymers are concerned. Furthermore, the amount of energy required for many of the 3DP processes is quite high in relation to the number of parts, again when compared against volume manufacture. Users must therefore consider the intrinsic value of parts before a commitment to build them is made.

6 Conclusions

The use of 3D printing can definitely be considered in a frugal manner. It is an enabler for design of low-cost solutions to important problems. 3DP is a technology that can provide such solutions at many levels, including high-end problems in industries including aerospace, volume consumer products such as mobile phone covers and hearing aids, and sociably responsible products such as prosthetic hands to be used in economically-deprived regions. 3DP can also be considered in a frugal manner in terms of building low-cost and accessible machines and using recycled materials.

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