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Sustainable Design: Using Physical Prototypes to Most Benefit Design Students and Environment?

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Abstract

After reviewing the main environmental areas of concern today, this paper will focus on waste management within the area of sustainability. For many years, as part of the design process, physical prototypes were a necessary. This was in order to prove a design's functionality and safety. They were expensive, time consuming and, by todays standards wastful. Often, once production began, they were scrapped. The necessity of a physical prototype outweighed all environmental considerations. In the 21st century, with the growth in Computer Aided Engineering (CAE), physical prototypes have nearly been replaced with virtual prototypes. The evidence is overwhelming as to the benfits of virtual prototypes to designers, designs and the environment. This paper will research and identify an area where physical prototypes are still beneficial, that of educating design engineers. A survey of mechanical engineering students over 5 years will identify a significant difference in the basic engineering knowledge of full-time engineering students when compared with their part-time colleagues. The use of physical prototypes can help reduce this difference. This paper argues that physical prototypes, under certain conditions, can reduce waste and still be sustainable.

Keywords: Sustainability, virtual, prototyping, design, education.

1 Introduction

Sustainablity is commonly accepted as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Jiang *et al.* 2021) (Han, J., *et al*, 2021). The United Kingdom (UK) Government Office for Science produced a paper in 2013 on sustainability and manufacturing (Tennant, M,. 2013).The paper makes it clear that without change, the following environmental issues are a real threat to the future:

- Global population rises.
- Greenhouse gases continuing to be emitted, average warming will be over 2℃, possibly up to 4℃ - 6℃.
- Material resources are likely to be scarce, posing significant problems for manufacturers.
- An increase in incidence of extreme weather events.

The recent COP26 conference in Glasgow, Scotland held hope for billions of people that a corner could be turned and their future prospects would improve. Some advances between nations was made but much is still to be done. This paper will consider sustainablity from the viewpoint of the design engineer and design education.

Today it isn‘t enough just to be a good designer. A good designer must consider the sustainability of their designs as 80% of sustainability impacts are determined at the conceptual design stage (Jiang, P., *et al*, 2021) (Han, J., *et al*, 2021). Badurdeen *et al* (2018) suggests an end-of-life (EoL) approach where the sustainability of a design is considered at the concept stage and thereafter throughout the product life. A product could have multiple lifecycles; reuse, remanufacture, recycled. Tennant (2013) highlights an important area of sustainablity, that of material resources. As design engineers, we want to use the limited resources as efficiently as possible, including minimising any waste.

The world we live in is changing at an exponential rate. For some people this is a good thing, they embrace change, for others, change disrupts their lives, it alters their status quo which makes them feel uncomfortable and nervous. The reality is, we cannot stop change, so it is better to embrace it and make it work for us. Historians categorize different periods in history by these changes.We live in the modern age, also known as the ‘Information Age’ (Gunner, J. 2008). The ‘Information Age’ can be divided into four information revolutions, writing, books, printing, and the digital revolution. The digital revolution today gives us telephones, computers, networks, internet, bandwidth, and electronic journals (Arunachalam, S., 1999). This is the age in which computer technology leads, and affects every aspect of our lives. For engineers, this is known as the age of Computer Aided Engineering (CAE).

CAE is used throughout nearly every phase of design and manufacture of a complex product. Components parts are designed using 3D modelling software which can be used to produce a virtual prototype. Once approved, the 3D models can be machined on Computer Numerical Controlled (CNC) machines, the programs being written by Computer Aided Manufacturing (CAM) software based on the 3D model (Rahimie, S., & Sunje, E., 2011) . Before CAE developed, components would be machined and a real-world physical prototype would be assembled to check for functionality and interference of parts. Today, these physical prototypes are rare and have been mostly replaced with virtual prototypes. Virtual prototypes bring many benefits to the design engineer, quick to produce, easy to edit, low cost, multi-users interconnected through the internet, and Finite Element Analysis (FEA) (Dieter, G., & Schmidt, L., 2013).

Historical ages are usualy named with hindsight, when its possible to look back and view a period of time in context with previous perods. COVID-19 has already changed the world we live in. For nearly three years the world has lived with a developing new language; lockdowns, vaccinations, boosters, omicron, asymptomatic, contact tracing, symptomatic, PCR test, herd immunity, social distancing, and varient are just a few examples. For the forseable future there may not be an end to the pandemic, rather, we may need to find a way to live with it. Could we be entering a new or different historical age? Lockdown changed education, students could no longer attend classes as the lessons moved to virtual, online. They no longer received the support of their peers in a classroom, they were working either alone or within a small bubble of peers. Teachers learnt new skills within a virtual classroom, break-out rooms, student

interaction, socializing, and chats (Swapnil, A,. 2020). Some unforseen benefits were found. Design in industry, which requires many specialist engineers is often arranged in teams. These teams, because of the geographical locations of its members often meet virtually. It is possible for a design team never to meet together in the real world (Design Council., 2018) (Sabbagh, K,. 1996). Lockdown has helped us all to develop the skills required to work as part of a design team, working 100% virtually.
After reviewing the use and need of prototypes by design engineers, this paper will detail the development of virtual prototyping, a subset of Computer Aided Engineering. After describing the use and benefits of virtual and physical prototyping and comparing them with each other it will show that, in the area of education, the use of a physical prototype can bring many extra benefits.

2 Computer aided engineering

Computer Aided Engineering (CAE) according to Kolbasin and Husu (2018) 'is a technology, the task of which is to facilitate creation, change, analysis, and optimization of projects.' The advent of computers with increasing computational power, graphical user interfaces, networking, and the internet has produced major changes in the way engineering design is practiced. As computers developed exponentially, so has CAE developed into nearly every field of engineering and has significantly assisted in sustainable designs. Early computers were mainly computationally intensive, allowing the design engineer to automate calculations using high-level languages such as FORTRAN (Formula Translation) (Bellis, M., 2019). Once an equation was entered, calculations could take many hours to produce a solution. This system was not very user friendly and required the operator to be specially trained in a computer language. The development of the microprocessor and the personal computer changed all that. These were designed to be user friendly, making the entering of equations and data easy and the calculations much faster. This made possible the development of software programs where calculations were easier to input, without the use of high-level languages. Added to this were computers with a graphical interface, allowing images and graphics to appear on screens. From these changes came, arguably, the greatest impact of CAE, the ability to produce 2D drawings using a personal computer. To produce 2D drawings, edit and print them has become common place today. The graphical interface developed into a specialist subsection of CAE and became known as Computer Aided Design (CAD) (Chen, Y. 2014) (Shigley, J. E., *et al*, 2004). 2D drawing programs developed into 3D modelling programs. These models are rich in intrinsic information that can be used for analysis, optimization, simulation, rapid prototyping, and manufacture (Dieter, G. E. & Schmidt, L. C. 2013). Other benefits of 3D modelling are Finite Element Analysis (FEA) to calculate stress in a component, Computational Fluid Dynamics (CFD) to simulate the flow of fluids, and tool path calculations for Computer Numerical Controlled (CNC) machines for manufacturing.
Between 1990 and 1994 the world witnessed a first. The aircraft manufacturer Boeing produced a design for a commercial airliner, the Boeing 777. The was the first, 100% paperless design. This was achieved using the Computer Aided Three-dimensional Interactive Application (CATIA) 3D Computer Aided Design (CAD) system. It linked all the design and manufacturing groups in Washington and suppliers of systems and components worldwide. At its peak, the CAD system served some 7000 workstations. Using the conventional paper design, it would be normal to experience interferences between components, costing many $millions to correct. The new system reduced re-working by over 50%. This is remarkable, especially when the Boeing 777 has more than 130,000 unique engineered parts. If rivets and other fasteners are included, that number increases to more than 3 million parts (Dieter, G. E., & Schmidt, L. C.

2013). Two computer programs were required, CATIA to produce the component parts, and Electronic Preassembly in the CATIA (EPIC) to assembly the parts together. Eventually, this made possible one vast computer simulation of the whole aircraft. This was an early example of Virtual Prototyping (VP) (Sabbagh, K. 1996).

3 Virtual prototyping

Virtual Prototyping is any prototype created entirely in a virtual space that does not involve physical contact with the object being designed, an exception is the use of haptic devices in virtual environments (Wang, G., 2002). Virtual prototypes assist in producing novel, unique and functional designs and in making the process of design more sustainable. Being virtual lowers waste by reducing design errors, functionality improvements which increases a product's lifetime, and optimisation to minimise required resources (Jennings, B., & Bourne, K., 2001). A part of virtual prototyping is the use of CAD, sometimes within a Virtual Reality (Coutts, E. R., & Pugsley, C. 2018). An example mentioned earlier was the Boeing 777, which combined two computer programs CATIA and EPIC. By combining these programs, virtual prototypes were created. To justify the extra expense of these programs the planners compared the Boeing 777 with a previously manufactured aircraft, the Boeing 767. They concentrated on the design of the doors. On the Boeing 767 there are two doors, passenger, and cargo. The doors, during the design phase required 1,341 modifications and iterations. The planner's put a dollar value on these modifications and came to a staggering total of $64 million. It was estimated that introducing virtual prototyping reduced modifications by 95% with a corresponding saving in $millions (Sabbagh, K., 1996). Compare the Boeing 777 savings with the astronomical costs of Concorde (see section 4) there can be little doubt of the financial saving using virtual prototyping. When compared with sketching, virtual prototyping systems improved the visualization and communication of designs (Robertson, B. F., 2009).
Another product, developed in parallel with virtual prototyping was computer simulation. The story of simulation started back in World War 1. Due to the heavy demand for pilots and the limited resources of flying schools, pilots were being sent into combat without adequate training. The resulting high casualty rate and accidents during training led to the development of the Link flight trainer. In 1929, Edwin Link invented a flight trainer that replicated a complete cockpit and controls that could produce the sensation of flying. This early simulation became known as the Link Trainer. Many examples of this trainer can be seen in aviation museums (Chihyung, J., 2015). The link trainer was the first practical aircraft simulator, over 10,000 were manufactured during World War 2. Between the end of the World War 2, and the 1960's the first flight simulators were used to train commercial pilots. Since then the technology has taken big leaps forward, making the modern flight simulator amazingly realistic in its recreation of real aircraft flights. These were the forerunner of what later became known as virtual reality.
In the last few decades, virtual prototyping has been taken from the computer screen and put into the world of virtual reality. This term was first used by Jaron Lanier who founded a company Virtual Programming Languages (VPL) research in 1984. Virtual reality is also known as 'Artificial Reality', 'Cyberspace' and 'Virtual Worlds'. Virtual reality is a computer-generated 3D environment that allow the user to enter and interact with alternative realities. Within this world haptic devices can be used. These make it possible, by using sensors, to apply a physical force in virtual reality that can be fed back into the computer program, thus allowing user interaction with the virtual world. Sound and even smells can be part of this world (Gilson, G,. *et al, 2003).*

4 Physical prototyping

During the development of a product, there was invariably a need to produce a single example or physical protype of a component or system before allocating large amounts of capital to new production facilities or assembly lines. A physical prototype was required to evaluate the design and troubleshoot any issues (Kalpakjian, S., & Schmid, S. R., 2006). This is still a time-consuming process but a vast improvement compared to the time and cost of remanufacture production tooling.
Traditional manual methods to manufacture a physical prototype can be used but will require vast amounts of time. To reduce the time to manufacture components for a physical prototype, rapid prototyping or solid freeform fabrication was developed (Coutts, E. R., & Pugsley, C. 2018). This technology can be classified into three major groups: subtractive, additive, and virtual.

- Subtractive – Process involves material removal from a workpiece that is larger than the final part. This approach requires skilled operators using material removal by machining and finishing operations
- Additive – Builds up a part by adding material incrementally, often in layers. To help the reader to visualize the process, imagine constructing a loaf of bread by stacking and bonding individual slices on top of each other.
- Virtual – Use of advanced computer-based visualization technologies. Complex software allows the user to create and manipulate components on a computer screen. More advanced versions will use headgear and gloves with appropriate sensors to let the user observe a computer-generated prototype of the desired part (Kalpakjian, S., Schmid, S. R. 2006).

There are many examples of rapid prototyping used to produce a physical prototype. The Ford Motor Company realized that to meet production goals, a physical prototype of the rear-wiper motor cover was needed for the 1994 Explorer automobile. Fords tooling supplier could not meet the deadline of six-weeks. From a CAD file a prototype was manufactured and fitted over the wiper motor. As is often found, the part did not fit due to an interference problem. The part was redesigned and the fit verified. The redesigned component was manufactured at 30,000 per month. The total redesign to production turnaround time was four weeks (Kalpakjian, S., Schmid, S. R. 2006).
Another example was the Anglo/French aircraft, Concorde. This early design, dating back to the 1950's was one of the most tested aircraft of all time. According to Mr. James Hamilton, who was the director-general of the Concorde division at the Ministry of Aviation from 1966 to 1970, test rigs were manufactured for everything. Concorde covered new areas of research in materials and aerodynamics and so prototypes had to be manufactured to test this new research and theories. The result was a cutting-edge aircraft design that is still admired to this day. The negative to this was the design and then redesigning, inflation, devaluation, changes in exchange rates, testing, flight testing were shown clearly in the increasing costs. In 1962 the estimated cost was £150-170m. By 1979 the estimated cost had spiraled to £1,129m (Owen, K. 2001). As can be seen from the example of Concorde, physical prototyping was an essential part of the design process but was not very sustainable due to the waste produced. Thousands of very expensive prototypes in terms of materials and cost were scrapped once the aircraft was flying. Modern methods have improved the situation. End-of-life (EoL) strategies during sustainable product design are applied. Rather than scrapping a prototype once its usefulness is at an end, multiple strategies are employed to reuse, remanufacture or recycle, thus minimising waste (Badurdeen, F., *et al*, 2018). An example is material selection. This was usually based on a materials properties. Sustainable material selection includes a materials origin. Does it come from a nonrenewable or renewable resource? New sustainable materials are being developed

by applying renewable resources. Bioplastics are produced by using renewable plants such as sugarcanes, corns, and potatoes (Han, J., *et al*, 2021). Rather than design just a product, designers proactively design a product lifecycle (Jiang, P., *et* al, 2021). Today the design process can be completed even faster, with computers and virtual prototypes.

5 Virtual v physical prototyping

The advantages of virtual prototyping and a virtual world far out weigh those of physical prototyping, the main advantages are:

- Reduce costs
- Reduce time to market
- Accurate
- Easy to change or edit
- Enable collaboration at the design stage
- Reduces errors in manufacture
- Finite Element Analysis (FEA)
- Mitigate material waste
- Allow early testing
- Reduce number of physical prototypes
- Improve operator safety and comfort
- Unravel design complexity
- Increase productivity and competitiveness
- Parametric modelling
- Optimization

(Teklemariam, H, G. *et al*. 2014)
(Walker, V. *Et al.* 2010)
(Coutts, E, R., & Pugsley, C,. 2018)

If you compare the above with advantages of a physical prototype there is a marked contrast:

- Improves feasibility
- Improves quality of designs
- Helps supplement mental models

(Coutts, E.R., & Pugsley, C., 2018)

Though the above list of advantages is not exhaustive, the contrast between the two approaches highlight the benefits of virtual prototyping when compared to physical prototyping. Note, the above list only states that the number of physical prototypes would be reduced. Despite the overwhelming evidence for virtual prototypes, there is still a requirement to produce physical prototypes. One area is in the field of higher education.

6 Physical prototyping and higher education

Educations needs to focus on both individual and systemic changes to resolve practices that are not sustainable (Kelly, M. & Alam. M,. 2009). It is vital that in all areas, including design, waste should be reduced, ideally to zero. The use of physical prototyping in education will produce better trained designers who for the rest of their careers will produce improved designs which will reduced net waste. Benefits of using physical prototypes in education were highlighted by Lemons (2010) who found that (physical) model building helped engineering design students generate design ideas. The visualization and evaluation were easier. Students were more aware of their creative thinking and design strategies. Earlier the term ‘haptic’ was used, the use of sensors to apply a physical force in a virtual world. In the physical prototype world, we can use the word ‘tactile’ which is something ‘designed to be perceived by touch’ (Oxford English Dictionary, 2002). It is not possible yet, in the virtual world to provide a full tactile experience achieved in the physical world. Not long ago, the importance of a tactile experience in learning was explained by lateralisation of the brain into two halfs, right and left (Petty, G., 2004). Individuals would prefer to use one side more than the other and this would determine the individual learning style. This theory is now considered as neuro-myth based on meta-analysis, which is the combined findings across multiple studies (Centre for Educational Neuroscience, no date). The Centre for Educational Neuroscience continues to show that, for the most successful learning to be achieved, learners require different learning styles which will suit one individual more than others. Analytical, logical, verbal, creative, emotional, visuo-spacial, all can be left, right or both sides of the brain. These learning styles can be achieved to a limited degree virtually, but are achieved better with a combination of virtual and physical. To give students a task that evokes feelings such as doing something physically, hands on, manipulating, moving, handling real objects. This can be achieved virtually, only to a limited degree (Centre for Educational Neuroscience, no date).

In engineering terms, there are significant differences between the virtual world and physical world in producing an assembly. To assemble or fix two components together in the virtual world is simply a matter of using ‘mates’ to tell the software that you wish to join this part to that part. There is no requirement to consider the method to join the parts together. Are they welded, bolted, glued, or pinned? The order that parts are assembled, virtually, does not matter. If one part, in the virtual world passes inside another part, or hits another part during movement, the virtual world will allow this to happen. This is one difference between a virtual model or prototype and the real world with a physical prototype. To successfully design an assembly virtually, requires experience. A physical prototype will teach students how to fix parts together and then assemble a system better than any virtual prototype (Zhong, Y., *et al* 2005). Practical work can lead to a deeper understanding of a concept and helps a person aquire specific techniques that become the tools of your trade (Bradley, S., 2012). The importance of practical training to students are; retains information for a longer period of time; increased active learning which has a grteater impact on knowledge; increased engagment; develop finer motor skills; encourages self learning; industry ready; practice makes perfect; builds inter-relation with theory (Benic, *et al*. (2018)

Most of us take our senses of sight, sound, touch, smell, and taste for granted. In the virtual world great effort is being made to incorporate these as realistically as possible. There have been advances made to augment virtual reality with elements of form, texture, volume, scale, and light where possible. These are the building blocks of learning. We used them when we were little, when we learned through play. Watch a child pick something up for the first time. They will turn it around and around, they smell it, they lick it, they hit it, and they stroke its surface. This is learning in its most basic form. As adults, we make ‘play’ with more sophistication, but we still learn using the same tools. The full benefit of these tools can only be found in a physical world (Merry, A., 2019). It is probably only a matter of time before all the above can be acheived in the augmented virtual world, making this world appear real. This could then be the end of all physical prototypes.

6.1 Student’s knowledge survey

During academic year 2016/17 a class of final year university students on a BEng (Hons) Mechanical Engineering programme in the United Kingdom (UK) was set a design challenge in one of their modules. The challenge was to design a three-speed gearbox for use in a metalworking lathe. Their designs were to be modelled using 3D modelling software and backed up with a written formal report, justifying decisions they had made. Over the next few weeks, as the designs progressed, the module lecturer, as he walked round looking over the student's shoulder noted that some students had decided to fix the gears to their shafts using a key and keyway. Of concern, was that some students had decided the key and keyway was to be square ended. This was based on an internet search. Keys and keyways can be square ended, if this can be justified, but makes the machining much more difficult and expensive. The normal design of a key and keyway would be round ended. This was the first indication of a lack of basic mechanical engineering knowledge. This lack of knowledge was repeated in many different areas. The lecturer decided to carry out a qualitative survey on the basic engineering knowledge of his students (Sole, M. E. Y., 2021). The survey consisted of 50 images of basic engineering components such as keyways, circlips, bearing, screws, bolts etc. and asked the students to identify the object in the image. The survey was conducted over the next five years and the results are shown in table 1 below:

Table 1. Student's Basic Engineering Knowledge

Academic Year	Students Total	Part-Time		Full-Time		% Difference
		Total Students	Average % Correct	Total Students	Average % Correct	
2020-21	73	8	96	65	82	14
2019-20	111	47	89	64	75	14
2018-19	115	44	93	71	60	33
2017-18	113	40	92	73	55	37
2016-17	114	41	86	73	37	49

The results identified a difference in the basic engineering knowledge between full-time and part-time students. In academic year 2016/17 part-time students identified correctly, on average 86% of basic engineering components. Full-time students achieved 37%. A difference of 49%. Many factors may be involved in producing this difference, but one factor was that part-time students, after spending one day a week at university would be spending the rest of the week at work, doing their job as engineers, building their basic engineering knowledge. They manufactured components, assembled them together as part of real, physical hands-on prototypes. Full-time students at the same time were building a different type of knowledge, a knowledge based on theory and computer simulations, designing mainly in the virtual world. They were rarely, if ever, required to physically produce components, or assemble them together as part of a physical prototype. This situation has created a difference in practical engineering knowledge between full-time and part-time students which has grown larger over the years. To address this, full-time students require real practical engineering, which could include manufacturing of real, physical prototypes (Benic, n*et al*, 2018).

3D modelling software and the virtual world undoubtedly bring many benefits and advantages to the design engineer. This unfortunately this does not apply to all areas. In education, 3D modelling has been found to exasperate an existing problem. The limited engineering knowledge of full-time students identified above, combined with methods employed to assemble a 3D model, and information from student's research based on the internet has created a perfect storm of difficulty for student design engineers. When set a design task, students will naturally turn to the internet to carry out a literature review. Identifying appropriate sources of

information is the first difficulty. Many sources can appear legitimate and appropriate but provide misleading information. The limited mechanical engineering knowledge of full-time students makes them more susceptible to using incorrect or inaccurate knowledge. The component parts of the design are created as 3D virtual components. These components are then assembled. In the virtual world, assembly requires just telling the software, join this part to that part by clicking on a mouse. The method of how to join these components is not necessarily required. Again, the limited knowledge of full-time students exasperates the situation as they may not even be aware of the right questions to ask. At a university in the UK, the final year students on a BEng (Hons) Mechanical Engineering programme can enrol in a competition to design and build a radio-controlled aircraft. Initially, after carrying out research, the basic design is created using 3D modelling software. Once completed virtually, the students then build their design, which will be a real, physical prototype. Students found the difference between virtual modelling and real, physical modelling to be vast. To make a real physical prototype rather than a virtual one, when educating students, especially full-time students bring many benefits and assists students in building the necessary basic engineering knowledge. To physically hold components, determine how to join them together, see how they fit into each other, brings the virtual components alive, helps the students see any problems with assembly. A combination of virtual and real-world engineering, a virtual prototype followed by a real prototype has been found to build the basic engineering knowledge base of design engineering students (Coutts, E.R., & Pugsley, C. 2018).
Students select a subject to study, such as mechanical engineering because it interests them, they empathise with it. Most, when younger will display a preference to practical learning, such as repairing cars and bicycles, making models, questioning how things work. This is something that is built into them, part of who they are. Theories suggest that people act in certain ways, learn in a preferred way because one side of their brain is more dominant than the other. The right side of the brain, according to Theodore (2020), displays creativity and artistic strengths which are good for being a designer, an artist, a writer. Countering this theory was the Centre for Educational Neuroscience (no date) who agree that we all have preferred learning styles, but these are not dependent on either side of our brain. The fact remains, that individually we all prefer to learn in particular ways. It has been suggested that students can be grouped by their preference to input an event. Petty (2004) suggests three preferences: visual, auditory, kinaesthetic/tactile. These preferences are not mutually exclusive, students can make use of all three. Engineering students tend to prefer learning kinaesthetically/tactile. This type of stimuli helps them to recall things later. Helps to retain things into their long-term memory. A physical prototype will assist students in building their engineering knowledge by stimulating their brains, fixing in their memories such things as size, weight, and feel. As their knowledge and experience builds they will be able to apply it more and more to things in the virtual world. It will enable them to make a virtual world appear more real.

6.2 Students' Fixation

When students are given a design problem, they can often suffer from fixation. This is when a designer unintentionally limits the number of ways, they can solve a problem. This can cause a reduction in novelty and creativity of ideas (Walker, V., *et al*, 2010). This can often be seen most during the concept stages of design, when initial ideas are sketched for the first time. This is a time, if possible, to think 'outside the box', to come up with wild, crazy ideas, that sometimes develop into functional designs. Student's often struggle with crazy concepts, and tend to stay with standard ideas, usually based on a search on the internet.
An example of fixation could be when a designer is exposed to several common solutions to a design problem. A designer may be inclined to build on these common concepts, concentrating

on small incremental steps rather than exploring alternative design solutions. Another example could be opposite of the previous example where a designer chooses to ignore a unique design solution in favour of exploring other design solutions (Perttula, M., Sipila, P., 2007).
The use of a physical prototype, according to Walker (2010) in early concept generation is one way in which the concept generation process could possibly be aided. This would be through exposure to new ideas, social motivation as real prototypes are created or through increased physical understanding of the problem. Usually, prototypes whether physical or virtual are produced much later in the design process. Walker (2010) suggests this has benefits in the early stage of design, the concept stage.

7 Conclusion

In the past, there was an undeniable requirement, as part of the design process, to produce physical prototypes. Today, with the development of CAE, physical prototypes have been replaced by virtual prototypes. Physical prototypes are used in a very limited way when a virtual prototype is not capable of simulating a design accurately or clients prefer an actual tactile experience. A survey testing the basic engineering knowledge of students studying a BEng in Mechanical Engineering was carried out over a 5-year period. Even though this survey was limited to student’s knowledge, it does provide an insight into an important issue that requires addressing. It was shown that in the field of education, physical prototypes provide many benefits to students and in the long run, also benefits the environment. The benefits are 1) The educational experience is stronger and helps students understand a design problem clearer. 2) A physical prototype helps build a student’s basic engineering design knowledge by helping to embed the knowledge firmly into memory. 3) When students physically assemble components together, they see the fit and the interaction between the components. 4) The physical prototypes required by students will tend to be less complex than protypes later in their careers. This will make them less expensive and quicker to produce. 5) Physical prototypes will make for better future design engineers, saving more time and money and resources when they embark upon more complex designs. 6) Fixation on design concepts can be reduced.
When teaching future design engineers, there are long terms benefits to using a real, physical prototype. These physical prototypes may produce a small amount of waste, but this will be offset by the savings the design engineers will achieve due to their improved design education. These gains, over time will result in a net improvement in sustainable products.

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