# REALISATION OF SELF-REPLICATING PRODUCTION RESOURCES THROUGH TIGHT COUPLING OF MANUFACTURING TECHNOLOGIES

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## Abstract

The purpose of this paper is to explore the implications of the tight coupling of manufacturing technologies and the extent to which it can facilitate the realisation of self-replicating production resources. This was explored through a three year programme of development projects where multiple 3D printing and milling machines were designed, built and evaluated with respect to their manufacturing capabilities and self-replicability. It was found that this tight coupling of processes increased functionality, self-replicability and consequentially utility of these machines. The project specifications were used to identify conflicting requirements and qualitatively assess their interrelationships. Further work will see this expanded into a quantitative model to identify where design effort should be focused and also theoretical limits of self-replicability. The principal social implication of this work is that non-autotrophic self-replication, upon which the RepRap philosophy is based, is largely dependent upon locally available technology and resources. Self-replication therefore becomes an affordance of not solely machine but also of environment.

**Keywords**: 3D printing, Open source design, Case study

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# 1 INTRODUCTION

This paper is a study of three Master's level Group Industrial Projects (GIP) undertaken at the University of Bristol between 2014 and 2016. The study seeks to explore the how the tight coupling of manufacturing technologies facilitates the realisation of self-replicating manufacturing resources. What follows is a short review of additive manufacture, self-replicating machines, RepRap, coupling of manufacturing technologies and hybrid manufacturing and how these frame the aforementioned research question. The final machines constructed by the GIP teams are then presented. They are compared quantitatively with respect to their self-replicability, stiffness and milling accuracy. Qualitative comparisons are made with respect to their manufacturing capabilities and how these are achieved, as well as design features such as frame design and materials. The design strategies of the teams are also compared in order to demonstrate progression of the approach to the design problem from year to year. The discussion looks at the conflicting requirements of self-replicating machines through analysis of the design requirements that are identified by the project teams. This is achieved by mapping the requirements using a cause and effect tree. The future outlook for self-replicating machines is also considered along with possible emerging technologies and how they may augment current levels of self-replication.

# 2 BACKGROUND

This section provides a brief overview of self-replicating machines, additive manufacture, hybrid manufacture, tight coupling of manufacturing processes and the RepRap project. It provides the foundations on which the direction of research of the student projects reported in this paper is based.

## 2.1 3D Printing / Additive Manufacture

Additive manufacture is achieved using various techniques such as fused filament fabrication, stereolithography, layered object manufacture, and selective laser sintering. It has many advantages over traditional techniques, such as being able to produce parts that are unrealisable through other methods and also rapidly produce prototypes. Drawbacks regarding entry level machines in-particular, include high material costs and lack of precision and repeatability in manufactured parts (Conner, Manogharan and Meyers, 2015).

It has captured the popular imagination as a ubiquitous manufacturing technology that will affect the way in which we consume and produce goods. In industry more than 60% of manufacturers have adopted the technology in some manner, with a further 25% planning to do so in the future (McCutcheon *et al.*, 2014). Outside of industry, there has been a large uptake of the technology by consumers and hobbyists. Studies have shown that a low end 3D printer such as a RepRap could save a US household hundreds to thousands of dollars per year and can payback its initial costs in as little as 4 months through printing commercial products for home use that would otherwise have been bought (Wittbrodt *et al.*, 2013).

Whilst a potentially powerful money saving tool in the developed world, its possible applications in the Global South are much further reaching. 3D printing has the potential to allow people access to consumer goods, that can greatly increase quality of life, without being tied into global production networks that currently dominate manufacture (Birtchnell and Hoyle, 2014).

A potential forerunner in achieving this is the Replicating Rapid Prototyper (RepRap) which is an open source 3D printer capable of manufacturing a proportion of its own parts. Its conception is detailed in the following section.

## 2.2 Self-replicating machines & RepRap

Machine replication theory largely comes from the work of von Neumann during the 1940s and 50s. His work on theories of self-replication postulated that self-replicating automata may be realisable (Merkle and Freitas Jr, 2004). Subsequently, much work has been completed in trying to prove the theory in practice by building an autotrophic self-replicator - something that remains unachieved.

Whilst research into artificial reproducers has focussed upon making a reproducer as autotrophic as possible, it is an approach that nature has almost abandoned. Almost all species are assisted self-reproducers. That is to say they are dependent upon other species in order to reproduce. So why not follow nature's example and design an artificial reproducer in a manner so that it is inter-dependant on natural reproducers? This was the approach taken by the designers of the Replicating Rapid Prototyper. It was designed to form a mutualism with humans where the machine would make its own parts and provide people consumer items in exchange for humans assembling and maintaining it (Jones *et al.*, 2011).

The first RepRap machine was built in 2007 and since then it's estimated that their numbers are now in the hundreds of thousands. This can be attributed to the open-sourcing of the technology and the large community of RepRappers that contribute to its development (Mohr, 2014).

Whilst a hugely successful project, it is currently not capable of producing many of its components as fused filament fabrication is not a suitable method for manufacturing them. This highlights a potential avenue for increasing its self-replicability; coupling additional manufacturing methods in order to increase the types of parts it can make.

### 2.3 Tight coupling of manufacturing processes & hybrid manufacturing

Hybrid machines are defined as those which integrate different processes within one machining platform (Zhu *et al.*, 2012). Hybrid manufacturing processes are defined by the International Academy of Production Engineering to be a process that combines two or more established manufacturing processes into a new combined set-up, whereby the advantages of each discrete process can be exploited synergistically (Lauwers *et al.*, 2014).

Based on these definitions, in the projects studied, hybrid manufacturing machines have not been developed. Instead what has been developed therefore are machines with tightly coupled technologies that allow multiple manufacturing processes to be carried out.

In a desktop environment a number of similar machines already exist such as the BoXYZ (BoXYZ, 2016) and ZMorph (ZMorph, 2016) that incorporate fused filament fabrication, laser cutting and milling. Consequentially it is proposed that tight coupling of manufacturing processes could add much to the versatility of a machine such as a Rep Rap by increasing the amount and type of components it can produce and hence increase its level of self-replicability. It is this proposition that is explored in this paper.

## 3 METHOD

In order to investigate the aforementioned proposition, a three year programme of development projects has been undertaken. The projects studied were Master's Group Industrial Projects (GIP) undertaken at the University of Bristol from 2014 to 2016. Groups consisted of 3-4 people. Projects were constrained by a budget of £600 and each had a strict deadline that corresponded with the end of the academic year. Students were given an open design brief to develop the RepRap and build on the work from previous years. All groups were encouraged to use analysis based approaches to justify design decisions and to increase self-replicability.

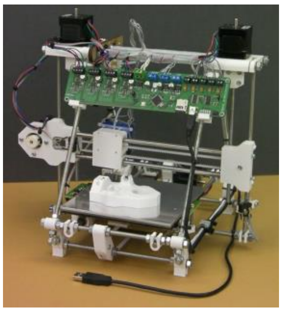
In total 3 projects of this form were run over consecutive academic years. From these, changes in project outcomes, the progression of thinking regarding design strategies, barriers to future improvements and advancements towards full self-replication can be observed.

## 4 RESULTS

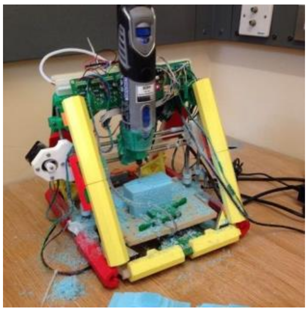
This section presents the results of the three different student projects. What follows is a brief overview of the various designs, a comparison of the design specifications and finally a summary of the design strategies adopted by the different teams. Information in the following sections is taken from the Master's theses submitted by the project teams (see Kho, Raines and Walmsley, 2014; Boxall *et al.*, 2015; Mathias *et al.*, 2016).

### 4.1 Design Overview

The projects were based on two different existing designs of RepRap, the Huxley (shown in Figure 1a) and the Mendel (shown in Figure 1c).

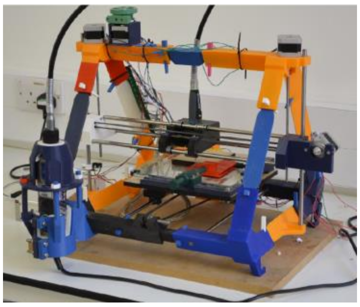


a) Huxley – First Generation

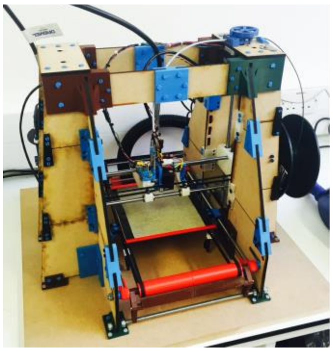


b) Holliger – Second Generation

c) Mendel – First Generation



d) Galen – Second Generation



e) Bertha – Third Generation

*Figure 1. Pictures of the finished machines*

#### 4.1.1 Holliger

The Holliger (Figure 1b) was developed from the existing Huxley (Figure 1a) in 2014. The end product was a CNC machine based on the RepRap Huxley with a mostly 3D printed frame held together by printed wedges with additional medium density fibreboard (MDF) cross braces. A directly mounted Dremel unit was used as milling tool. Whilst cuts were made in MDF, it was only able to produce test pieces made of foam.

#### 4.1.2 Galen

The 2015 team developed the Galen (Figure 1d). Design lessons were taken from the Holliger and taken forward to develop the existing RepRap Mendel (Figure 1c). The design consisted of a fully 3D printed frame but with re-designed and re-positioned joints and larger structural components. The Galen is capable of both milling and printing but to switch processes manual tool changing is required. Entirely 3D printed fixtures were developed to secure workpieces for milling, and a universal bed was developed that allowed both milling and printing.

A Dremel was again used as the milling tool but via an extension allowing the bulk of the tool to be mounted on the frame and not on the X-carriage. Compliant printing materials were used to mount the Dremel to reduce the effect of vibrations on the machine.

The end result was a machine that could 3D print and mill MDF.

#### 4.1.3 Bertha

Continuing on from the work in the previous year, the 2016 design team developed Bertha (Figure 1e). Like the Galen, Bertha's frame is 100% self-replicable but constructed from MDF with printed connectors and fasteners. The use of MDF as a frame material over printed plastic greatly reduced the cost of the frame. The machine is capable of both printing and milling with automated tool changeover. Automated removal of printed parts was achieved through the use of a flexible bed that allowed parts to be peeled off. Automated stock clamping for milling was also achieved.

### 4.2 Solution Specification Comparison

This section provides quantitative data describing the capability of the different designs, which provides the basis for conclusions and discussions.

The importance of this section is that from the quantitative values the different machines can be directly compared and progression from year to year can be observed giving insights into the implications of different design strategies. Results are shown in Table 1. The contents of this table are considered in greater detail in Section 5.1. All values are taken from other work (see Kho, Raines and Walmsley, 2014; Boxall *et al.*, 2015; Mathias *et al.*, 2016).

*Table 1. Specification Table*

| Project | Percentage Self Replicabilty‡ % | Frame Stiffness Y Direction N/mm | Frame Stiffness X Direction N/mm | Milling Accuracy mm | Cost £ |
|---|---|---|---|---|---|
| Huxley | 38 | - | 17.2 | - | 360 |
| Holliger | 54 | 20.4 | 16.1 | 0.25* | 362.50† |
| Mendel | 38 | 25.9 | 17.7 | - | 450 |
| Galen | 50 | 44.5 | 36.1 | 0.27 | 480 |
| Bertha | 73 | 100.3 | 79.4 | 0.11 | 394† |

*Accuracy achieved at different cut depth and feed rate to other milling accuracies so cannot be directly compared

†Not including price of milling tool

‡% self-replicability by part count and not including fasteners

## 4.3 Design Strategies

This section defines the different approaches employed by the teams to solve the design problem. It also looks at how the strategies progressed year on year in response to lessons learned from the previous year. It is interesting to note how the development in design strategies correlates with the increase in performance from year to year.

A number of general aspects were common across the three projects. Experimental work looked at cutting forces, identifying natural frequencies of the machines and static load testing. Finite element analysis and other forms of simulation were used to justify design decisions and optimise structural components. Once built, the machines were extensively tested for performance with the aim of quantifying improvements in design from generation to generation.

The three projects had similar overarching goals which were implemented in different ways. These goals were to:

- **Increase manufacturing capability**: Allowing the machine to perform both additive and subtractive manufacturing processes.
- **Increase self-replicability**: Through increasing the number of components manufacturable by the previous machine and increasing manufacturing capability.
- **Increase stiffness**: The key difference between additive and subtractive manufacturing techniques is that additive experiences negligible forces during operations whereas the forces experienced in subtractive processes are large. Therefore increasing frame and overall stiffness was crucial.
- **Ensure machines is suitable for domestic use**: By keeping the overall size of the machine low and using manufacturing technologies safe enough to use in the home.

### 4.3.1 Holliger

The design strategy taken by the group behind the Holliger project involved taking the existing RepRap Huxley and developing an entirely 3D printable, stiffer frame. The primary aim was to create a machine capable of both milling and 3D printing (though this wasn't achieved). Secondary aims were to increase self-replicability and ease of assembly whilst maintaining a compact size that would be suitable for desktop use.

### 4.3.2 Galen

The Galen project team sought to apply the lessons learned from the development of the Holliger and apply them to the RepRap Mendel - a larger 3D printer.
Having proved the feasibility of a 3D printed frame, the team looked to a new frame design that would be stiffer and easier to assemble. From static testing of the Holliger it was found that whilst the members

themselves were stiff, substantial bending occurred in the joints. Frame design focussed therefore on minimising the number of joints and maximising joint stiffness.
As the Holliger did not manage to achieve both printing and milling, an aim for the Galen group was to develop a machine that could carry out both processes. This required the redesign of the X-carriage (tool carrier) and subsequent design of a holder for the milling tool that would minimise the effect of vibration.
It was also necessary to develop a universal bed that would permit both milling and printing. This was achieved with 3D printed jigs and fixtures which would allow the holding of stock and be suitably stiff.

#### *4.3.3 Bertha*

Building on the work from previous years, the Bertha project team looked to re-work the approach to the frame design. The Galen team were able to build functional pieces made of wood with their prototype, therefore the Bertha team pursued a wooden frame design. The previous team had also found that printing of large parts was fraught with failures and was incredibly slow. For this reason team Bertha opted to build the large structural pieces of the frame out of MDF whilst 3D printing the joints. They also changed the overall shape of the frame which in previous years had been prismatic resulting in reduced stiffness in one axis.
There was also a notable change in focus towards set-up and manufacturability. The manual tool changeover required on the Galen was time-consuming, driving the need for automated tool switch-over. This drove the design of a changeover system that could accurately and reliably change between manufacturing processes. The project also sought to re-design the workpiece clamping system. The 3D printed jigs and fixtures were slow to use and adjust which drove the need for automated part removal. This would increase efficiency by reducing down time and also allow autonomous production, with no need for human interaction between prints.

## 5 DISCUSSION

This section draws on the results presented in section 4 and also presents the conflicting requirements of self-replicating machines.

### 5.1 Results

Table 1 shows that from the base Huxley and Mendel to the final Bertha, a two-fold increase in self-replicability can be observed as well as a near five-fold increase stiffness. Functionality is also greatly increased. The Huxley and Mendel are capable of only 3D printing whereas Bertha can 3D print, mill structural components out of MDF to an accuracy of 0.11mm, automatically remove printed parts, automatically clamp stock and automatically switch between manufacturing processes. With the price of milling tool included, Bertha achieves this for roughly the same price as the Mendel.
Design strategies were based upon the overarching goals (defined in section 4.3) and also from lessons learned from the previous projects. Proof of a concept one year would lead to it being utilized to its full potential in a subsequent year. For example the Galen proving the capability to mill structural components out of MDF led to the following project team subsequently designing a frame of which the large structural parts are made of MDF.
The performance of all the completed machines can be deemed to be adequate as they either match or better the performance of similar machines on the market for a similar price. The projects can therefore be concluded to have realised the production of useful machines. Due to the open source nature of the designs and a competitive market for low-end manufacturing machines, it is arguable that they are not marketable. This should not detract from the projects' usefulness and success as, in being open source, they adhere to the RepRap philosophy.

### 5.2 Conflicting requirements of self-replicating machines

Based on the specifications from the three generations of machines, nine interrelated requirements can be identified. These are defined in Table 2 along with two additional requirements; made of specialist components & materials and value. The former serves as an indicator of the effect of designing for manufacture and assembly. When requirements are considered collectively they represent the challenges and trade-offs in realising self-replication.

*Table 2. General design drivers identified from the specifications from the group projects*

| Driver | Definition |
|---|---|
| **Complexity** | A metric comprising of part count and the variety of components in the machine |
| **Cost** | Cost per machine |
| **Self-Replicability** | The percentage of its own parts the machine can manufacture |
| **Accuracy** | The accuracy of parts produced by the machines |
| **Stiffness** | The machine's resistance to deflection under loading |
| **Multi-functionality** | Based on the number of processes a machine can carry out, on which materials and to what accuracy |
| **Size** | The size of the machine with respect to volume and mass |
| **Ease of Use** | The ease with which the machine can be assembled and operated |
| **Made of specialist components and materials** | The incorporation of materials that are for example high strength and low weight or facilitate simplification of use or manufacture |
| **Value** | A measure of the capability and usability of the machine against its cost |

Figure 2 shows a cause and effect tree that identifies the relationships between the different requirements of a self-replicating multi-process manufacturing machines. Arrows with a plus sign denote an augmenting effect from one to another and arrows with a minus sign a reducing effect.

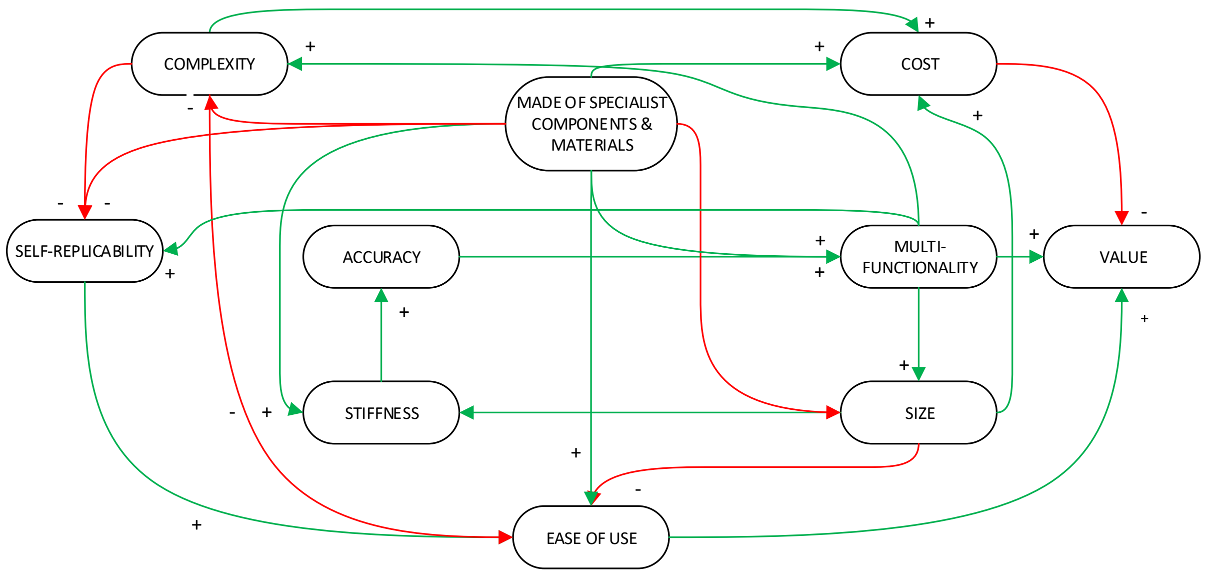
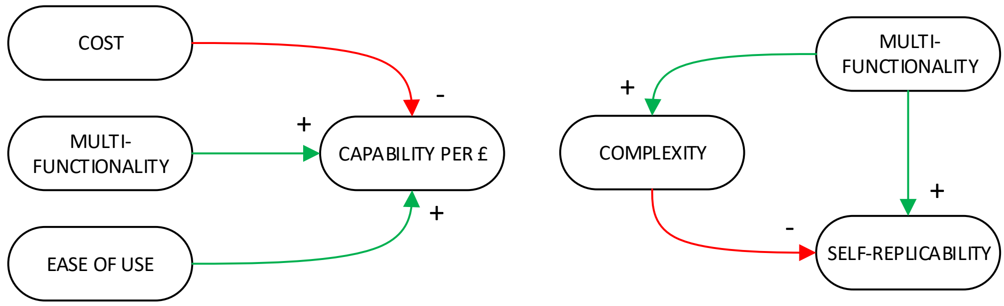



*Figure 2. Cause and effect tree for the various requirements of a self-replicating manufacturing machine*

A number of important relationships can be observed within this diagram, two of which are shown in Figure 3. The first of which is that the perceived value of the product is dependent upon its multi-functionality, ease of use and cost. The second is how an increase in multi-functionality simultaneously augments and reduces self-replicability. Another notable influence is that of the 'made of complex materials' has a great effect on a number of different factors and appears to have a net neutral result on the overall perceived value of the product.

In the above analysis we have considered a manufacturing centre as a closed system. However it may be more useful to consider it as an open system that is linked to equipment and raw materials already available in an area. Careful analysis must then be carried out in order to identify whether a given alteration in functionality will, for example, cause a net increase in perceived value. For example adding milling functionality does not add value if wood is not available at an affordable price as a raw material. The projects have taken different approaches to increasing the self-replicability of the machines but really this is inextricably linked to the environment in which they are to be used, therefore ranking one design over the other becomes very situation dependant.




a) Contributing factors to capability per £ for manufacturing centre

b) Effect of increasing multi-functionality

*Figure 3. Notable findings from the cause and effect tree*

### 5.3 Future outlook for self-replicating machines

In the section 5.2 we identified conflicting requirements in self-replicating machines such as the RepRap. Increasing the functionality of a machine will increase its complexity which in turns makes it more difficult to self-replicate.

Given this, and also that the RepRap is a self-replicator that is inter-dependant on humans, generally speaking, what is important is appropriate self-replication. Or in other words that the RepRap is capable of making parts that are not widely available locally, out of raw materials that are. This is something that will change from region to region.

Steps currently being taken to increase self-replication include the development of conductive inks and printers that can manufacture parts with embedded electronics, such as the Voxel8 (Voxel8, 2016). Whilst this is useful, the conflicting requirements that we have already identified suggest that it may not actually increase self-replicability.

A different approach to increasing self-replicability involves building with digital matter as opposed to a continuous manufacturing process such as 3D printing. This would allow reversible assembly of components where parts can be reused when the machine is decommissioned. This approach to manufacture has several advantages. One key advantage is in theory allowing positioning of components more accurately than the positioning accuracy of the machine and thereby eliminating accumulated error, which becomes significant with larger parts (Gershenfeld, 2012). This technique has already been used for the assembly of large structural components (Gershenfeld *et al.*, 2015) , the fabrication of individual electronic components such as capacitors (Langford, Ghassaei and Gershenfeld, 2016) as well as the assembly of larger electronic systems out of small, modular, electronic blocks (MacCurdy, McNicoll and Lipson, 2014).

## 6 FURTHER WORK

Beyond the existing three projects described previously, further GIPs at the University of Bristol are expected to be undertaken, focusing on self-replicable machines. Within these further development could be carried out in the same vein as the projects already undertaken, by looking to increase manufacturing capability, self-replicability and stiffness whilst ensuring the machine remains suitable for domestic use. In section 5.2 however, we identified that there exist conflicting requirements and their interrelationships are complex. It was also identified that self-replicability is an affordance of not only machine but also of environment. Therefore research should be directed towards developing manufacturing resources that are appropriately self-replicable. That is to say that they can manufacture their own parts that are not manufacturable or available locally.

Additional further work will look to expand the cause and effect tree from section 5.2 into a dynamic model that will simulate the conflicting requirements and how these can effect uptake of the technology and subsequent product development.

## 7 CONCLUSIONS

This paper has explored, through a study of a three year programme of development projects, the implications of the tight coupling of manufacturing technologies and the extent to which this facilitates the realisation of self-replicating production resources. It was identified that 3D printing is a powerful manufacturing technology that already has the potential to save consumers money and allow people in the developing world to access consumer goods that they otherwise wouldn't be able to. RepRap is highlighted as a forerunner in promoting accessibility to this technology due to it being open source and capable of printing many of its own parts. It was subsequently suggested that through coupling manufacturing processes, the versatility and self-replicability of RepRap could be greatly increased.
An overview of the three machines developed was given and their specifications and designs strategies were contrasted. Year on year, an increase in self-replicability can be observed with the final project, Bertha, capable of manufacturing 73% of its parts compared to 38% for the base RepRaps. The final machine is capable of 3D printing, milling structural components out of MDF to an accuracy of 0.11mm, automatically removing printed parts, automatically clamping stock and automatically switching between manufacturing processes - achieving this at approximately the same price as a stock RepRap Mendel.
The design specifications for the three projects were used to draw out key requirements and the interrelationships between these were identified. From these it was concluded that there is no clear direction for future research as the relationships are complex. In order to increase self-replicability as well as utility of manufacturing resources, the environment in which they are to be used must be considered - as to be of maximum use they must provide capability that is not already locally available. The identification and mapping of these requirements serve as considerations when designing for self-replicating machines.
Further work will see the development programme continue into its fourth year. Additionally, the relationships identified between the various requirements of self-replicating manufacturing resources will be expanded into a dynamic model. It will quantify the manner in which the requirements interact and also the way in which they influence the uptake of technology and direction of research.

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All underlying data are provided in full within this paper.