Advantages of Using Hybrid Manufacturing Platforms to Realize Decentralized Manufacture

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ABSTRACT

Manufacturing has traditionally been the domain of centralised factories, set-up and optimised to make a sole product or product-range. Whilst the in-house efficacy of such systems has been greatly improved due to lean six-sigma methodologies, the wider scale distribution and supply system has undergone little to no transformation over the past century. Previous research pertaining to distributed manufacture, cloud-manufacture and reconfigurable systems has provided several decentralised models using traditional manufacturing capabilities. Though to date they have not been fully realised due to practical limitations. This paper outlines the scope for hybrid manufacturing platforms – using a plurality of processes on a single motion platform, to manufacture products in a decentralised network. Social, economic and environmental ramifications of adopting such a system under particular use cases, such as in shops, community areas or in individual households, are highlighted. The combination of several key processes, including measurement, will allow users to manufacture parts with minimal intervention. A move to personal fabrication would allow greater personalisation and convenience for the end user; however, the issues of copyright and loss of economy of scale would inhibit mass uptake in the near-future. Growing interest by enthusiasts and early adopters will continue to make an impact on the way the populace views manufacture.

1. INTRODUCTION

Manufacturing has been the backbone of industry for centuries. From pre-industrial revolution there is a transition from custom, bespoke manufacture, to batch and then mass-production in the twentieth century. More recently manufacturing can be split into three epochs: Pre-Numeric Control (NC) (pre-1960), Computer Numeric Control (CNC) (1960-1990) and Knowledge based (1990 onwards) [1]. The first epoch depicts mechanical control, with use of transfer lines to reduce cost and the presence of only local competition – with no demand for product variation. The second epoch encompasses the invention of NC tools (NC). NC positively impacted quality and production rates, in addition to giving rise to waste reducing philosophies such as Lean, Total Quality Management and Six Sigma. Machine tools are considered as a single entity. The last epoch is characterized by rapid progress in computer and information technology. Competition in manufacturing is now on a global scale and every effort is made to produce high quality products and afford quick responses to a continuously changing market [1].

This progression has led to large-scale factories, which are set up to efficiently mass-produce several dedicated products [2]. Raw materials and sub-assemblies need to be transported and stored on-site, along with manufactured products when processed. Finished products need to be shipped to subsidiary warehouses and distributed, before eventually ending up on store shelves. This logistic cost is further compounded by the trend for outsourcing manufacture to the Far East. Hesse and Rodrigue [3] investigated freight transport and logistics showing that despite logistics becoming more technologically efficient, the cost in the manufacturing sector is spiralling upwards. In 2000 the US manufacturing sector spent US$1,006 billion on administration, transportation and inventory carrying costs ($39, $590 and $377 respectively). This is up from US$668 billion in 1990 ($26, $351, $291 respectively).

The approach of large dedicated factories has worked to drop the price of goods due to economies of scale. However, the cost to the environment is large with 14.2 million tonnes of airfreight passing through EU airports in 2010 alone [4]. In addition to this the environmental effect of freight transport impacts the UK's climate change policy [5].

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Piecyk and McKinnon [6] state that currently 255 billion tonne-kms are transported on Great Britain's road network, leading to 19.3 million tonnes of CO_2 emissions. Their worst case scenario predicts an increase of CO_2 by 56% in 2020. With the inconvenience, cost and impact on the environment it is worth investigating alternative models to a centralised manufacturing system. This paper first discusses theoretical and practical approaches towards realising decentralised manufacture. It then outlines novel use of hybrid technology to make this realisation more practical. Various options for implementation are highlighted, before discussing the ramifications and main barriers to entry for such a system.

2. CURRENT THEORIES ON DECENTRALIZATION

2.1. THEORETICAL PROPOSALS

The alternative to a centralized, mass-production factory is a transition towards a decentralized model. Management and Human Resource systems have been restructured in the last twenty years to stay globally competitive. Latest advances in communication technology have enabled team-based management methodologies to be implemented, such as Just in Time (JIT) and Flexible Manufacturing Systems (FMS) [7]. These methods have shifted manufacture of standard products in high volume to providing a wide variety of products in low volumes.

Analogous to the service sector, the manufacturing sector is experiencing a shift to decentralisation. Several methods to achieve this have been suggested, such as flexible manufacture. In this model production lines are modular: so that several products are manufactured on a single factory line, without taking up the space of a dedicated line. This modular approach allows sections of the line to be interchanged with other sections (i.e. a milling station replaced by a grinding station) between products—minimising downtime [1]. Koren *et al* [8] describe the key characteristics of a reconfigurable system as: Modular, Integrable, Convertible, Diagnosable and Customizable. The combination of reconfigurable manufacture with reconfigurable design allows for mass-individualization and customer-led modular open-architecture products [9].

Another approach is cloud manufacture, proposed by Xun Xu [10]. In this scenario manufacturing is treated as a service. With the Internet geared towards a cloud computing system, it is a natural progression for this approach to also be adopted and used within manufacturing context. A user can request a manufacturing operation at a specific geographic location using a URL embedded command. For this system, manufacturing facilities can be remotely located – like server farms. In order to send the relevant information to the manufacturing site, not only will the geometric design be necessary, other information such as tolerance, manufacturing techniques and materials will be required. Existing standards will not sufficiently carry this information, so ISO 10303 "Standard for the Exchange of Product model data" (STEP) should be used [11]. Once the STEP-based manufacturing command is sent the part can be made remotely and then posted to the user. This system increases logistics, but may cut down on lead times.

2.2. REAL-WORLD EXAMPLES

Whilst previous approaches have been theorized, real-world examples exemplify the potential of decentralized manufacture. The first of which is RepRap – an open-source, self-replicating rapid prototyping machine [12]. Conceived at the University of Bath in 2007, it uses fused filament polymers to produce engineering components. Currently it can reproduce 57% of itself and users are encouraged to make a child RepRap from the parent machine. In this way the initial capital cost is minimized – based solely on raw materials. It is the ultimate goal of this project to move from a system of factory production of patented products, to one of personal production of un-patented products with open specifications [12]. The current cost of a RepRap system ranges between US$300-600. Due to this low price point and a sense of global collaboration, a thriving community has grown up around the RepRap movement.

Another example involves low-cost manufacturing facilities that are available for the public. This initiative is called a Fab Lab (an abbreviation of fabrication laboratory) [13]. The Fab Lab is a small workshop that contains a number of basic manufacturing equipment, typically a 3-axis CNC Mill, vinyl cutter, laser cutter, 3D printer and circuit board production facilities. The project has its roots in MIT and has rolled out worldwide to 50 locations, offering a low-cost community driven solution to manufacture. The Fab Labs are free (or low cost) and are used for education and small-scale prototyping for both individuals and small businesses. Fab Labs in developing countries are used for local humanitarian projects.

3. ADVANTAGES OF USING HYBRID MANUFACTURE IN A DECENTRALIZED CONTEXT

As outlined, the theorized models and real-world applications have had minimum impact on the manufacturing industry as a whole. One fundamental similarity between the schemes is that they are based on traditional serial processes, applied sequentially. For instance RepRap comprises one technology—fused deposition modeling (FDM), and though Fab Labs house a plurality of machines, they are only enacted one at a time, with manual intervention and change. This requires a competent operator to be present. These shortcomings mean that accessibility for everyday users is inhibited by a lack of manufacturing knowledge.

There is a clear niche for combining multiple processes on a single platform, in this context termed Hybrid Manufacture. Zhu *et al's* [14] comprehensive review considers a hybrid machine to: "combine two or more manufacturing operations, each of which is from different manufacturing technologies and have interactions with and influences on each other". This clarifies the existing definition of Hybrid Manufacture from three main variants proposed by the International Academy of Production Engineering (CIRP) [15]. By combining different processes, products that traditionally require several machines to manufacture can be made on a single machine. For instance, an additive process, such as FDM or laser cladding, could be combined with a subtractive process, such as milling or turning. This would enable a user to download a design and produce a part, needing only to supply the raw materials. Lights-out manufacture (autonomous from the user) is completed with smart process planning systems for deciding when to add and when to subtract material [16][17].

Here it is proposed that if measurement is considered constituent of hybrid manufacture, a major limitation of decentralized manufacture can be overcome – verification of quality. In a centralized factory, quality assurance (QA) is achieved through manual gauging and measurement via coordinate measuring machines (CMMs). Finished parts are verified and reworked or scrapped if necessary. For confidence in parts made to specification and manufactured in a decentralized location, there must be a means of measuring in situ, and the capability to rework the manufactured part if necessary. A hybrid manufacturing system will allow this to be achieved divorced of the user.

4. TARGET AREAS FOR HYBRID MANUFACTURE IN DECENTRALIZATION

Traditionally manufacturing is completed in large-scale factories, so a transition to manufacturing outside of this environment is difficult. However, here it is suggested that there are alternate viable avenues to explore, with manufacturing investigated at a personal, community-driven and industrial level, summarized as follows:

- Option 1: Move manufacture to local factories – and utilize Just-in-Time (JIT)
- Option 2: Have manufacturing in shops (professionally run)
- Option 3: Have manufacturing in community areas
- Option 4: Have personal fabrication in the home

Each option yields different benefits and each subsequent option offers more of an impact on how society would have to adapt to incorporate such a type of production.

4.1. HYBRID MANUFACTURE IN LOCAL FACTORIES

Manufacturing in remote large-scale factories yields scope for hybrid platforms. Not replacing traditional CNC machines entirely, an additive/subtractive machine could successfully supplement existing equipment. Small-scale, agile hybrid machines could reduce inventory stock by making necessary sub-assemblies on demand. With only raw material necessary, the level of stored inventories can be vastly reduced. If there is a further move towards standardizing materials, governed by availability, rather than designer's prerogative (similar to standardized sizes), then the number of stored materials can also be reduced. This perfectly complements a Just-in-Time (JIT) system [18], but instead of being delivered just in time, they can be made just when needed instead. This differs from the current JIT practice of ordering a part just in time to reduce inventories, as transport and storage of the part is not necessary - reducing pressure on logistics. As an additional benefit of this system if a design change was necessary, all that is needed is an updated design for the updated part to be manufactured. In a traditional system any sub-assembly prior to the design change that is in stock would be wasted, or phased out, and time required ordering the latest version.

4.2. HYBRID MANUFACTURE IN SHOPS

In certain applications it might not be necessary to bulk produce products in factories then distribute them to shopping outlets. Instead products can be made in store on demand. An example of this using current technology would be a car repair shop. If a car needed a replacement part, instead of ordering it, it could be made using a laser sintering process on demand. This process might not be suitable for every part, some of which are designed to be forged because of the imparted stress and strain characteristics; however, other parts are more suited to this process such as casing and trims. A car part ordered using the present system may take several days to be transported by a local distributer, especially if the part is rare or out of production and requires procurement from a specialist dealer. A customer could choose to have the part produced in-store so time would be saved by reducing transportation. This would particularly be useful for one-off out of production parts. With a typical laser scan rate of over 100mm/s [19] a standard part can be made in a couple of hours, only requiring a downloadable design and a stock of raw material.

A second example using current technology would be a furniture shop. Rather than having a catalogue of designs that are stored in flat-pack form in a large warehouse, the shop could employ a manufacture to order system. In this system the customer could pick a design from a brochure and have a machine behind the scenes laser cut the flat pack in real time. Once packaged it is ready for the customer to take away. This cuts down on the storage space afforded by the company, as only raw material is necessary. It also prevents items being out of stock, or damaged in transit.

In the near future when hybrid-manufacturing technology develops and matures, not only will a mixture of hard materials be machinable on a single platform, but electronics will also be imbedded. Already printable electronics are being realized [20] and in time they too can be integrated on a hybrid manufacture platform. When this becomes viable and drops to a realistic price a range of shops will be able to manufacture products, both electrical and not, on demand. All that will be necessary is a design and raw materials.

4.3. HYBRID MANUFACTURE IN COMMUNITY AREAS

Two extremes of manufacturing practice, traditional factories and personal fabrication, have been commonly discussed in journals and the media; however, it is the middle ground that is relatively unexplored: community-based efforts. If the economic reality prevents home users from having individual fabrication facilities, there could instead be facilities that are shared by a local community. This idea follows on from Fab Labs [13] that have been set up worldwide, but instead of a myriad of manual machine tools, community areas can be fitted with hybrid platforms. These platforms can be accessed and used by the general public, and as they operate in a lights-out mode, the user would only need to ensure raw material and a design before leaving it to work.

4.4. HYBRID MANUFACTURE IN THE HOME

At the other extreme, residential-based personal fabrication can be discussed. This idea has been proposed in various forms over the past 40 years [21], [22]. Household printers are commonplace, but if the additive/subtractive hybrid machines can be cost engineered and reduced to a desktop footprint, then household 3D manufacture is possible. All that is required is a downloadable design and raw materials. Hybrid machines currently exist, but are too large and expensive. These issues only apply to the first generation of machines and will be overcome in the future. Malone and Lipson [21] compare the possible uptake of home manufacture to the uptake of home computing in the 1970s. The MITS Altair 8800 is highlighted as sparking the home computer revolution [23], costing US$400 (approximately US$2000 in 2005 dollars). It then describes the creation of a hobbyist's desktop fabricator kit which costs $2,300. This shows that the realm of low cost, hybrid platforms is attainable.

5. RAMIFICATIONS

If a move away from centralized manufacture was taken, there will be major social, environmental and economic ramifications. A discussion of which is illustrated in the following section:

5.1. SOCIAL

A large impact will be created by moving manufacture nearer to the end users. First, and foremost, there will be a change in the way goods are purchased. The general public is familiar with the convenience of online shopping; however, this is coupled with a wait between purchase and delivery. This appears at odds with the impatient nature of today's dynamic society. By moving manufacture locally, the convenience of ordering something online and picking it up immediately can be combined.

If a decentralized approach is taken, space will need to be allocated to manufacture in the house. Whilst this might not be a problem in suburban areas, in smaller inner-city flats the space cost of housing a $500mm^3$ footprint machine, as well as raw material, may be impractical. Even if a community model is adopted space will have to be allocated. This could be a section of a local shopping centre, or community centre or a dedicated building. Hybrid machines supplementing industrial applications will appear invisible to the end customer, though there may be changes to the production pipeline.

Personal fabrication implies manufacture will become more individual with a mixed social impact. The general public will be directly involved in production – something the majority have been sheltered from before. Some individuals may not physically be able to make their own products, unless the system was completely automated, and even then it could still prove problematic. This makes home manufacture less likely, but doesn't limit hybrid applications in a commercial environment, where members of dedicated staff carry out the operations.

The positive aspect of moving production closer to the end customer makes the option of personalization attractive. Personalization of products can be achieved easily by adapting a superficial part of the design, be it colour or the addition of a name. This itself prompts the question of who owns the design. The rise of personal fabrication will require copyright law to be reviewed. If a product is made and the user has direct access to the design, there would be no facility in place to stop the user to making an unlimited number of products (making the design worthless). However, if the purchase is for one product the design will have to be kept separate from the end user, adding a layer of inaccessibility. Bradshaw, Bowyer and Haufe [24] have investigated the legal aspects concerning the rise of 3D printing and have concluded that currently home users do not typically conflict with Intellectual Property, but larger commercial organizations might. The issues involved in this mirror Digital Rights Management in the music and film industries.

5.2. ENVIRONMENTAL

A move towards decentralization will have significant benefit for the environment. By cutting out transport of sub-assemblies and finished products there would be a reduction in CO_2 from reduced transport. Another benefit of hybrid manufacture means parts can be made using a combination of additive and subtractive processes, so they can be made with less material. This is due to the ability of structures to be internally honeycombed instead of being made from solid material. Smart algorithms are being developed to analyze when to add material and when to remove material. This will dramatically reduce material waste, as well as reduce energy required to run separate machines [16] [17][25].

In order for decentralized hybrid manufacture to become practical standardized materials will be required. It is implausible for individuals to stock various materials, so designs will have to involve only a subset of a select few. This can be advantageous as the standardized materials can be those that are more environmentally friendly, either through embedded carbon or required machining. This is already the case to a certain extent in industry with particular grades of aluminum and steel favored over others.

5.3. ECONOMIC

The economic ramifications of the proposed systems are polarizing. If manufacture does take place in the home or local community there is less cost associated with transportation and inventory, which could be passed onto the consumer. However, as previously illustrated, factories have become highly efficient at mass production of thousands of a single product and by moving away from this set up there will be a loss of economies of scale. There will also be a reduction in cost of rare and out of production parts, as all that will be needed is a digital design to reproduce the part. Companies can also save money by reducing the size and number of warehouses.

Though there is the loss of economies of scale the individual will only be purchasing the design and the raw materials to make the product. The user will also foot the cost of running the machine, but still the price of a product will be primarily dictated by what the design is deemed to be worth. The use of standardized material which has been suggested, similar to standardized sizes will also reduce cost. These materials can be selected for their attribute/cost ratio. Also by using only a few common materials the associated costs of design and storage will reduce.

6. BARRIERS TO ADOPTION

The main barriers to adopting a hybrid platform for decentralization will be discussed below, with rebuttal where possible:

Table 1. Barriers to adoption of a decentralised manufacturing model, with associated discussion.

Barriers to Adoption	**Discussion**
Operator skill level	The average user cannot cope with anything more technically sophisticated than an inkjet printer; though this may only be a problem with home manufacture. The solution to this can be one of two approaches. First the system can be designed to only be used by skilled members of staff, or overseen by a technical member of staff in a community centre (in a similar fashion to supermarket self-service tills). Secondly, the systems can be designed to operate completely lights-out. If this is successfully realized the user would only need to download the design, ensure raw materials are present and leave to manufacture.
Required Post-processing	As an example, sintered metal parts will need to have support material removed. This could be an issue depending on the products opted to be manufactured. A hybrid platform could be able to post-process certain applications (using both additive and subtractive heads). Alternatively products manufactured could be narrowed to only those not requiring post-production.
Material limitations	In order for home fabrication to become practical most designs should be limited to a few standardized materials. This will insure that products work as intended when a user makes them. It will also minimize the storage space afforded to raw materials – a premium in a private home. The actual decision of which materials to be selected is out of the scope of this paper, but a suitable starting point would incorporate a machinable and SLS suitable grade of stainless steel, aluminum, titanium and an ABS polymer.
Safety Considerations	The processes may not be suitable for a domestic or shop floor environment. This is an understandable concern and to be met the machines would need to operate in lights-out. With operations taking place automatically, when safety barriers and locks are engaged. This removes the user from the machining operations.
Quality of parts	Industry is organized around process control solutions; it is debated whether quality assurance can be guaranteed in a private environment. This again will be determined by the level of automation afforded by the machine. Quality can be assured through the use of in-process inspection.

7. CONCLUSION

A move towards a decentralized manufacturing society unveils exciting possibilities. Prior to the invention of hybrid machines personal fabrication was limited to either an additive machine or a subtractive machine. In this regard practical products can only be produced using several machines, with their specific associated costs, space and noise. An individual would need space to locate these machines and the knowledge to use and transfer partially finished parts between them, which is clearly impractical. However, with a self-contained hybrid system, personal fabrication becomes a blackbox system: raw materials and design are input, and after a length of time a product is produced. Whilst an integrated electronic product is still several years from realization, a product machined with several features, from several materials is possible with current technology [26]. For those willing or able to implement home manufacture there will be opportunities for the convenience of internet retail, with the immediacy of traditional shopping. However, this service will remain expensive for the early adopter until it is implemented on mass. Up until that point it will be a niche opportunity for product personalization for the enthusiast. Although, parallel to the enthusiast, industries that this technology would be used for first would be high-value manufacturing and bespoke manufacturing.

Most commercial success in the future, with hybrid technology can be found using cross-process platforms in stores in industry. This will make production lines leaner using JIT to make components as they are needed, rather than ordering them in and storing them separately. Another avenue of commercial success is possible in shops, first as a novelty, but then as a viable marriage between the virtual and physical retail world. In store production machines will allow users to manufacture their products in real time at retail outlets.

There are also possibilities in production of car parts and of specialized items. Traditionally rare and out of production parts would cost a premium to find and acquire; however, with decentralized manufacture they will need to only be stored digitally and be made when needed. Adoption of this, and the other proposals, will reduce transport, slashing the US$1,006 billion the United States spent on logistics and inventories in 2000, to the cost of transporting and storing raw materials alone. Whilst not economically beneficial for standard car parts, cost, time and convenience will be increased for rare and out of production parts.

Overall decentralized hybrid manufacture presents promising opportunities to the enthusiast, but no real financial incentive to the early adopter. The best application of the hybrid platforms would be in supplementing existing industrial processes and use as a marketing opportunity for retail stores - as in-shop real-time production facilities for customers. If these proved to be successful, then there may be cause to roll out decentralized production capabilities to local communities.

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