ATKINS: Manufacturing a Low Carbon Footprint

Zero Emission Enterprise Feasibility Study

Project No: N0012J

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Loughborough University

BOEING

DELPHI

MCP GROUP

BENTLEY

econolyst taking a closer look

Perkins CATERPILLAR®

RENAULT F1 Team

Virgin atlantic

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Executive Summary

This ATKINS Feasibility Study report has shown the significant potential of using metallic Rapid Manufacturing (RM) as a method for "Moving towards a Zero Emission Enterprise". ATKINS is a holistic project, concerning the design manufacture and distribution of components utilising RM as an enabling production technology. Using background and case study research the study has investigated the use of additive manufacturing techniques (polymeric and metallic) as a method for enabling optimal design, manufacture and distribution options for manufacturing companies.

The ATKINS Feasibility Study has shown the promise of using optimal design tools to enhance component parts and the products that they constitute. An example metallic component was investigated using design optimisation methods (such as computational fluid dynamics (CFD) and finite element analysis (FEA)), resulting in a component design that could not be manufactured by traditional subtractive or forming techniques. The "optimal" design showed a weight and material saving of almost 40% over the original component, which also translates to BREW savings during the manufacture, the use-phase of the product lifecycle and the distribution of the components.

For typical manufacturing volumes of 100,000 p.a. the ATKINS study has shown for the metallic component, possible BREW savings of 503 tCO_2e, 23 tonnes of water, displaces 157 tonnes of virgin material and saves 640 kg of potentially hazardous materials. These savings are realised due to the combination of RM with optimal design methods. Further savings of energy and landfill waste can be realised through the development of digital, distributed supply chains that RM can enable. ATKINS has identified that a single distribution warehouse contributes 5.2 million lorry km p.a. (7,240 tCO_2e) and 66 tonnes of waste to land-fill. The investigation of polymeric RM has shown that considerable landfill is produced as the materials utilisation rate is much lower for polymer systems when compared to metallic RM. As such it is the recommendation of this report that metallic RM be the focus for the Full Stage ATKINS project.

The design and RM of components will also have a great impact on the energy consumption of produces during the use-phase of the product life-cycle. This will be of particular importance to the transport sector. Savings in CO_2 emissions through the use of optimal designs to lightweight vehicles can reduce the fuel consumption of vehicles particularly those used in road and air transport. Reducing the weight of a long range aircraft by 100kg results in a 1.3 $MtCO_2e$ saving over the lifetime of the aircraft, the equivalent of saving $2.5 million worth of fuel.

The holistic approach taken in this Feasibility Study, which will be carried to the Full Stage project, provides benefits throughout the product lifecycle, from raw material utilisation through to the use phase. End-of-life considerations are not of concern as the materials used are those common to current recycling operations.

CONTENTS

1 Introduction

This report aims to outline the findings of the feasibility study project: “ATKINS”. The report will focus on the investigation of additive manufacturing techniques, commonly referred to as Rapid Manufacturing (RM), as a method for affecting the production of components and products. Particular emphasis on the implications for “moving towards a zero emission enterprise” will be considered.

The aim of ATKINS is to fundamentally migrate the design, manufacturing and distribution of goods and components away from the energy-intensive methodologies that are used today to a more sustainable method of production, service and distribution to the consumer. This low-carbon design, manufacturing and service philosophy will be enabled by the unique characteristics of RM. Current products are generally wasteful in all aspects from design & manufacture to the final distribution to the consumer / customer. This is mainly a consequence of conventional processes that restricts our current design, manufacture and supply chains as follows:

– DESIGN: Current products are far from optimal. The requirement to Design for Manufacture (DFM) dictates that over-weight; sub-functional components are manufactured that are inefficient in their operation. Although complex geometries such as honeycomb structures and micro-lattices could be advantageous to the weight of products for example, their complexity and cost of manufacture often results in components being manufactured from solid material instead. This is both wasteful and increases the weight of component parts. The function of component parts are also compromised by DFM, as current machining and moulding operations introduce constraints such as material wall thickness and the position of structural ribs and bosses. Again affecting both the efficiency of material usage and the subsequent part weight.

– MANUFACTURE: Many of today’s manufacturing processes are highly wasteful in their operation. Destructive manufacturing techniques, such as machining, result in the removal of large amounts of bulk material in order to produce the end-use part – often machining operations can result in over 90% waste material. Additionally, forming techniques such as casting and injection moulding require the production of suitable moulds and formers that expend significant energy, limit geometrical freedom, extend manufacturing lead times and result in multi-stage processes.

– DISTRIBUTION: The requirement to locate manufacturing at the site of, say, the injection mould tool or high speed machining centre requires that an expensive supply chain and transportation network is necessary. This requirement adds considerable energy costs to the product and, ultimately, the environment.

In contrast, Rapid Manufacturing offers many unique traits. RM processes are capable of producing virtually any complexity of geometry where there are virtually no DFM restrictions – therefore, highly optimised geometries could be manufactured at no extra cost[1, 2, 3]. Also, the flexibility and re-configurability of the processes (especially powder based technologies) enables the same machine to be used for the manufacture of a whole host of different geometries for a range of applications and sectors from bio-medical, automotive, aerospace, consumer and sports, amongst many others. Moreover, RM offers the potential to change the paradigm of service and distribution with opportunities for producing affordable, highly complex, custom products at locations at or outside the conventional factory – possibly by the distributor, retailer or even the customer. However, though many benefits potentially exist, RM is currently a nascent technology that is being used by a small number of pioneering organisations. In order for the benefits of RM to be realised by the wider UK manufacturing community, significant research issues need to be overcome. The following objectives have been identified for the Full Project stage:

1. Products/Design – Truly optimised products can be designed that are more energy efficient during operation.
2. Processes – Optimised RM processes will allow significant efficiencies to be accrued at the manufacturing stage compared to conventional manufacturing.
3. Waste – Substantial reductions in, and the potential elimination of waste.
4. Logistics – Digital supply chains coupled with distributed manufacture will challenge conventional wisdom and reduce logistical requirements where component data can be sent via digital links rather than as physical objects and produced on-site when required.
5. Whole Life Cycle – Significant reductions in greenhouse gas emissions (GHG) over the whole life cycle of the product will be achieved (by reduced product weight, optimised efficiency, less waste, more re-use of raw material, energy efficient manufacturing and reconfigured supply chains).

These Full Stage objectives directly align with those used during the feasibility study. Reducing the carbon footprint of part manufacture and distribution will be crucial of the future sustainable manufacturing aspirations of the UK. Using RM as the enabling technology, ATKINS will provide a route for the substantial reduction in energy required for the manufacture of components for a host of sectors and applications and will provide fully optimised products that maximise their own efficiency.

The purpose of this feasibility study is to demonstrate the concept of RM as a viable method for reducing the carbon footprint of manufacturing enterprises. The following objectives contribute to this ideal and have been investigated during the feasibility study:

1. Investigate the use of RM in design in order to produce an optimised component as a demonstration of how RM can best be utilised
2. Investigate the possible advantages and disadvantages of RM over “traditional” manufacturing practises in terms of waste: solid, liquid and energy.
3. Evaluate the distribution options for RM, particularly the possibility of distributed manufacturing and it’s impact on logistics.

The objectives have been investigated using a series of work packages (WP) tailored to the individual objectives in question, each of these WPs have fed into this final report detailing the outcomes of the study and possible impact for manufacturing organisations. This final report has been structured as follows:

1. Introduction
2. A review of the current state-of-the-art in terms of sustainable manufacturing practices with particular reference to RM
3. Feasibility study methodology
4. Results & discussion, including;
    a. Major environmental impacts
    b. Potential for supply chain restructuring
    c. Technological innovation
5. Conclusions and recommendations

The feasibility study has been designed to analyse RM and traditional manufacturing practices using the requirements of the 5 BREW metrics defined by the Department for Environment, Food and Rural Affairs, (DEFRA) these metrics are as follows:

BREW 1. Water-use reduction
BREW 2. Landfill diversion
BREW 3. Reduction in hazardous waste
BREW 4. Virgin material displacement
BREW 5. Reduce energy consumption

2 Review of Prior Art

A review of the current state-of-the-art follows. Importance is given to the effect of manufacturing on the environment (in a UK context) and a review assessing the impact of traditional manufacturing practice and RM on the environment.

2.1 UK Energy Emissions

Greenhouse Gas (GHG) emissions are defined as the amount of Carbon Dioxide equivalent (CO_2e) emitted to the atmosphere. CO_2e needs definition as different gases have different CO_2e levels. CO_2 has a global warming potential (GWP) of 1, this is a multiplication factor for the gas and relates the severity of the emitted GHG to CO_2. There are 6 direct GHGs shown in Table 1 with their GWP multiplier.

Gas	Nomenclature	GWP
Carbon Dioxide	CO_2	1
Methane	CH_4	21
Nitrous Oxide	N_2O	310
Hydro-fluorocarbons	HFCs	140-11,700
Per-fluorocarbons	PFCs	6,500-9,200
Sulphur hexafluoride	SF_6	23,900

Table 1. Direct GHG including GWP[4]

In 2005 the total emissions of direct GHG for the UK[i] were estimated to be 655.4 Mt CO_2e the constituents of this figure are displayed in Table 2.

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[i] Including all estimated GHG emissions from the Crown Dependencies and selected relevant Overseas Territories.

Source Category	Mt CO_2e
Energy	563.4
Industrial Processes	27
Solvents and other product use	0
Agriculture	44.9
Land-change and forestry	-2.0
Waste	22.1

Table 2. Aggregated emission trend per source category for 2005[4]

The ATKINS feasibility study is concerned with three categories that will be affected by the move to RM: Energy, Industrial Processes and Waste. Additionally, the category: *Manufacturing, Industry and Construction,* also contributes to the Energy source of GHG. The Transport sector is a market where ATKINS could have significant impact. In terms of contribution, road transport is by far the largest, though aviation has the fastest growing contribution (163% growth 1995-2005[5]), the design possibilities of RM could be significant on the weight and therefore energy consumptions of vehicles (accounted for in the Energy category).

Industrial Processes (4% of total UK GHG) includes GHG emissions related to non-energy related emissions from mineral, chemical and metal production. All manufacturing industries require material for conversion into products or components and as such is of importance for ATKINS. The waste sector (3.4 % of total UK GHG) accounts for GHG from solid and liquid waste disposal, for example from waste incineration.

2.2 Environmental Studies on Traditional Manufacturing

2.2.1 Machining

First and foremost, machining is a subtractive manufacturing technique that manipulates material through a series of cutting, milling and grinding operations. Inherently, more material is required than is used in the final product. In the aerospace sector, this is known as the “buy-to-fly” ratio of a component. For high-value aerospace components manufactured in expensive metals, material buy-to-fly ratios of 15:1 are not uncommon (15 kg of material to produce 1 kg component)[6]. This uses more virgin material than required (BREW 4) and results in increased energy usage during the recycling of excess virgin material and swarf, (BREW 5). Management of swarf production[7] can reduce machining times, lower waste disposal costs (cutting lubricants affect the price of swarf) and reduce storage capacity. One technique to reduce swarf is to implement near-net shape techniques and thus eliminate as much raw material usage as possible. However, net shape manufacturing systems, *i.e.* RM, have not yet been considered. Importantly, existing near net shape operations such as casting and forging limit the design possibilities.

In addition to the metal usage aspects of machining, one of the necessities of machining operations is the use of cooling lubricants at the cutting face in order to increase cutting speeds, reduce tool wear and provide accuracy and surface finish characteristics[8]. Work, carried out by Klocke and Eisenblatter[9] has highlighted the increasing economic and environmental concerns of using cooling lubricants (CL). Figures based on the German machining industry showed that over 75,000 tonnes of CL were consumed during a single year (approx. €100 Million). Of this quantity, approximately half were water miscible products mixed at 3-8% concentrations making emulsions of around 355,000 to 947,000 tonnes. An estimated 350,000 tonnes of used emulsion and oil based CL plus grinding slurries and filter materials required disposal on an annual basis. It was estimated that CL represented around 14% of the work-piece related manufacturing cost (higher than personnel and material costs combined). The use of CL has both an effect on BREW 1 and BREW 3 as CL contain a number of constituents including lubricants, emulsifiers, anti-corrosives, antifoams, biocides and fungicides. All of these elements have led to health and environmental concerns[10]. Recent developments in near-dry machining acknowledge that there are high costs of CL and are attempting to reduce their use[11]. However, at one of the UK's most modern engine machining facilities, 1.2 million litres of CL are in circulation, with the system costing £8 million to install.

2.2.2 Casting

Metal casting operations are formative in nature and require the production of tooling in order to operate, with the metal feedstock heated to a molten consistency in order to be poured into the relevant tool or die. By it's nature, casting is energy intensive as material needs to be kept molten prior to pouring. An example of the energy usage from the Aluminium die casting industry has been studied by Brevick et al.[12]. Two facilities were studied one a "low volume" producer and the second a higher volume producer. The low volume producer (6.8 million tonnes p.a.) received 90% of material in molten form (10% as ingot) with an energy consumption of 3.2 kWh per kg of material (1.4 kg CO_2e). This results in a total GHG emission of approximately 9,500 tCO_2e p.a. The higher volume manufacturer (25 million tonnes p.a.) had higher capacity holding furnaces and receives all material as molten Aluminium. Their energy consumption was approximately 0.5 kWh per kg (0.21 kg CO_2e). However, even with this more efficient operation the annual energy costs just for holding molten material accounts for over 5,000 tCO_2e p.a. In terms of waste material, the average casting yield for the two plants were around 70% of total material, with a scrap rate of 7%. These figures all contribute to BREW 4.

In addition to the energy consumption of holding molten materials, tooling will be required for the casting process. Normally this tooling is machined for die casting operations, and as such is subject to the environmental concerns for machining (shown in section 2.2.1). Furthermore, moulding normally requires release agents to be used to remove the component from the tool. As such additional resources and hazardous substances go into the manufacture of these release agents adding to the overall environmental burden of the process.

2.2.3 Injection Moulding

Injection moulding is a traditional method of producing high volume net shape products from, in the main, polymer materials. The vast majority of energy used (60%) during the process is consumed by the injection moulding machinery[13]; with further energy used by ancillary equipment such as water chillers and compressors (9% and 3% respectively). Typically an injection moulding machine will use 1.2 – 2.2 kW/kg of polymer processed[14]. A typical 500g moulding in Polypropylene equates to around 0.38 kWh/component or 0.78 kWh kg^{-1}. Many of the studies in developing injection moulding to use less energy during production ignore the whole lifecycle of the production process, namely, they do not consider the pre-requisites for injection moulding such as tooling and, in addition, do not consider the water usage (used for cooling the moulds) or the hazardous substances such as mould release agents etc.

2.3 Design Potential of RM

One of the largest drivers for the potential uptake of RM is the design area as the traditional necessity for Design for Manufacture (DFM) are removed. DFM limits what can be produced by a particular process, for example, in injection moulding split lines, draft angles, wall thicknesses, and re-entrant features are all issues that require attention when designing for the manufacturing process. With RM, in the main DFM criteria can be ignored and designers can design what they want or need rather than what the manufacturing system is capable of producing.

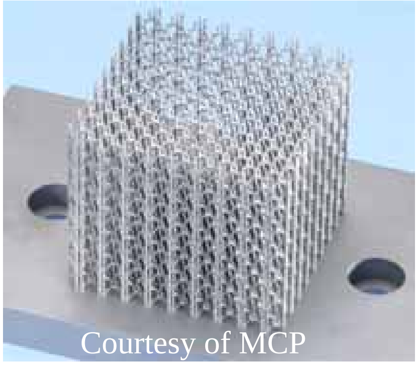

Figure 1. Example of possible structure manufactured using RM.

RM therefore allows the optimisation of components for their allocated task and, due to the geometrical freedoms, allows the production of these parts. Potentially, this also has a strategic fit with the area of eco-design. Eco-design is the relationship between the product and it's whole lifecycle, from raw material extraction, processing, useful lifetime to final disposal[15]. The geometrical freedoms allowed by RM will be a powerful addition for the eco-designer, particularly if recyclable and re-usable materials are available for RM. In effect, the eco-designer will be able to reduce the environmental burden of a component during it's life phase. This is normally the most energy intensive (BREW 5), and thus RM will help contribute to more efficient products through reductions in material usage (BREW 4) or energy consumption during production and/or through the life phase of the component. In terms of disposal, the use of RM and the possibility of consolidating an assembly of components into a single part has already shown promise for end-of-life disassembly[16] as not only does the process reduce the assembly operation but also reduces the material count for that assembly (BREW 2).

2.4 Effect of RM on Business Processes and Supply Chains

The application of RM techniques hold a number of advantages for manufacturing enterprises[17]. The effect of RM on inventory has been identified by Walter et al.[18]. The application of RM for suitable parts and components especially those that are of low volume but high value can result in a significant reduction in stock costs and inventory levels. The ability to produce components to order is an inherent quality associated with RM. As such, the parts or products required can be stored as low value raw materials and the stock value is reduced to that of the raw material and any obsolescence risks associated with the part or product design are eliminated.

As RM has a low labour requirement, implications on the manufacturing location will occur. The ability to produce RM parts locally will also have implications on the current globalisation culture of manufacturing business. As mentioned previously, the overriding cost for RM production is not labour, but the machines and materials necessary for production[19]. Indeed Walter et al. have stated that a single operator is able to efficiently manage several machines. For this reason, the migration of manufacturing operations to low-wage countries can be challenged especially for low volume and customised products and, with the advent of more capable machinery, high volume products in the long term.

2.5 Environmental Studies on RP

Many of the systems under development for RM have developed from existing RP equipment; they use similar materials and processes to manufacture products and components in an additive fashion. Three polymer systems have been evaluated for their environmental impact including stereolithography (SLA), laser sintering (LS) and fused deposition modelling (FDM). A review of the available literature now follows with emphasis on the criteria set out in the BREW metrics.

2.5.1 Energy Consumption

Work by Luo et al.[20] has begun to quantify the effects of RP systems on the environment using the Eco-Indicators (EI) model developed by Pré Consultants[21]; the model contains over 100 indicators for commonly used materials and processes and the higher the indicator the greater the environmental impact. The case studies have presented data and EI's for the three principle RP systems, namely, SLA, LS and FDM. Using data derived from the machine manufacturer for the build process, data for the energy consumption of three different RP systems SLA, LS and FDM has been calculated. Energy consumption rates (ECR) per kilogram of material consumed are shown in Table 3.

	Stereolithography SLA 5000	**Laser Sintering Model 2500**	**FDM 8000**
ECR (kWh/kg material)	20.70	29.83	23.08
kg CO_2e per kg material consumed	9.73	14.02	10.85

Table 3. Energy Consumption Rate (ECR) for typical SLA, LS and FDM equipment

These energy consumption rates have been converted to kg of CO_2e emissions using conversion factors for delivered Grid Electricity taken from the Carbon Trust[22].

Further work by Mognol et al.[23] has analysed the energy costs of three different RP systems an FDM 3000, 3D Systems Thermojet and EOSint M250 (a LS-type system). A common test piece was produced in 9 different orientations to ascertain the mechanism for energy usage during builds. For Thermojet and EOSint M250 the energy consumption is governed by the build height of the component. Increases in total energy consumption for these two technologies are influenced by component or build packet size. FDM realised a different mechanism, whereby the principle energy consumption indicator was the amount of supports required for the part. Table 4 shows the extremes of energy consumptions for different orientations on the three systems.

RP System	Electrical Energy Consumption (kWh)	
	Min	**Max**
Thermojet	2.1	3.8
FDM 3000	0.5 (+4)	1.25 (+4)
EOSint M250	32	56

Table 4. Total energy consumption for Thermojet, FDM 3000 and EOSint M250

There is a noticeable difference between the EOS machine and the Thermojet / FDM. This was attributed to the 200W CO_2 laser used to fuse the metal particles in the systems. Whereas the Thermojet and FDM systems heat a wax/polymer material requiring less energy. It is worth noting the EOS machinery is not state-of-the-art, and that most modern metal sintering machines use more efficient Yb-fibre lasers at 100W.

2.5.2 Metallic Systems

Little study has been performed on the environmental aspects of metallic additive systems. Essentially, metal systems are split into two technological categories, powder feed and powder bed. Powder feed systems feed a stream of powdered metal into a melt pool created by a high intensity laser beam. Whereas powder bed systems operate in a similar method to laser sintering in that a layer of powder is laid into the build chamber and then consolidated using a scanning laser system. Examples include MCP Realizer (SLM), EOSint M270 (DMLS), Phenix and Concept Laser. Such methods have been recognised as future manufacturing processes for high value metallic components. Particular notice has been paid to components manufactured from high value metals such as Ti-6Al-4V, which are difficult to machine and are expensive in raw form[24].

The only available data on environmental effects of metallic RP has been performed on a powder feed system known as Direct Metal Deposition (DMD) as a method of repairing or remanufacturing tools or dies[25]. The opportunities for reducing the environmental burden of these processes have been noted and are illustrated in Table 5.

Process	Opportunities for reduced environmental burden (aligned to BREW metrics)
Casting	Air/water emissions and energy consumption from furnace and mould material handling operations (**BREW 1 & BREW 4**); solid waste from discarded mould material (**BREW 2**), general footprint of factory operations and associated overhead (**BREW 4**).
Forging	Energy consumption (**BREW 4**); hydraulic fluid use and spills (**BREW 1 & BREW 3**); conversion coating use (**BREW 3**); metalworking lubricants and fluids (**BREW 1 & BREW 3**); footprint and/overhead (**BREW 4**); tool production and disposal (**BREW 2 & BREW 4**).
Machining	Energy consumption (**BREW 4**); production and handling of waste chips (**BREW 2 & BREW 4**); metalworking fluids (**BREW 1 & BREW 3**); tool production and use (**BREW 4**); on-site waste water treatment (**BREW 1 & BREW 4**).

Table 5 Traditional manufacturing operations and associated environmental impacts, adapted from Morrow et al.[25]

According to the US environmental protection agency (EPA) the activities shown in Table 5 release a significant percentage of the nation's GHG, consume large amounts of energy and are among the most significant polluters of freshwater systems[26]. The opportunities for additive type technologies to replace the wasteful processes outlined in Table 5 are clear, and importantly, are not only related to tooling but also end-use part manufacture.

One of the major characteristics of metallic RM is the use of powdered material as feedstock for the machinery. These powders are often produced through gas or water atomisation and the energy usage in the production of these powders is of concern when analysing the whole lifecycle of a metallic RM product. However, if the metal in question is directly atomised after the melting, refining and re-melting stages then the specific energy consumption (for H13 tool steel) equates to around 15 MJ/kg (or 1.8 kg CO_2e/kg), compared to plate production at 20 MJ/kg (2.4 kg CO_2e/kg); therefore a 25% saving in CO_2e can be made over the traditional route to raw material for the two different raw material processes.

Metallic RM systems are able to process a number of materials, not just tool steels; these include Ti-6Al-4V, Stainless Steels, CoCr, with Aluminium under development. The availability of Titanium alloys and their costs is a particular concern for aerospace companies. Titanium is, due to costs and methods of extraction, expensive both financially and environmentally. Titanium is produced from the abundant raw material *Rutile* (TiO_2), of which the extraction of pure Ti has been investigated for a number of years as the energy and labour requirement are considerable. The Hunter and Kroll processes, developed in 1910 and 1940 respectively,[27] are still the most common methods of production. Both processes require high energy input to produce $TiCl_4$ (heated to around 1000°C) and reacting with Mg/Na (800-900°C). Additionally, the two process are batch processes which results in a sponge like Ti which is then subsequently processed to form into an Ingot. A further refinement of the Hunter process is known as the Armstrong process. The Armstrong process produces Titanium through the continuous reduction of $TiCl_4$ vapour through Na.

The Kroll and Hunter processes are both expensive an inefficient[28] that consume significant amounts of energy. A move away from these pyrometallurgical processes is to use a solid electrolytic process. This has been developed by Fray, Farthing and Chen[29]; and is known as the FFC Cambridge[30] process. The process uses TiO_2 as the solid cathode and then a molten salt as the electrolyte to leave pure Ti at the cathode and O_2 at the anode. Ti produced using the FFC process can either be in a powdered or sponge form, the microstructure of which is in the 1 – 100 micron range. This process removes the need for producing $TiCl_4$ and thus reduces the energy consumption of the entire process. Likewise the process produces powders directly from ground rutile. The use of rutile as the starting material allows a better guarantee of powder shape and size as ceramic materials are more easily ground than the more ductile metal. Additionally, work by Titanox[31] is looking at a batch production process that uses less energy and chemicals to produce Ti powders.

It is envisaged that the coupling of these new raw material extraction techniques with metallic RM could offer significant challenges to the existing metal part production supply chains, particularly for high value metals such as Ti.

3 Feasibility Study Methodology

The methodology for the ATKINS feasibility study has been designed to highlight the differences between conventional (formative and subtractive) manufacturing and RM. ATKINS has attempted to monitor the effects of RM both up and down-stream from the point of manufacture. The feasibility study work-packages (FSWPs) have been carried out with industrial partners in order to develop a more thorough understanding of where ATKINS can affect manufacturing enterprises that are attempting to become zero emission.

3.1 FSWP1 Design for Low Carbon

FSWP1 focused on the development and use of optimisation techniques for improving the carbon footprint of an individual component. A component was selected for it’s suitability and impact with regard to increasing efficiency of the system or reducing the CO_2e burden of the component (i.e. reducing weight). The design exercise has been carried out with Delphi Diesel Systems (DDS) and the BREW metrics have been used as qualifiers to assess potential improvements or drawbacks of an RM system. The case study was based around a typical DDS component; a diesel pump front-plate. An image of the original design is shown in Figure 2.

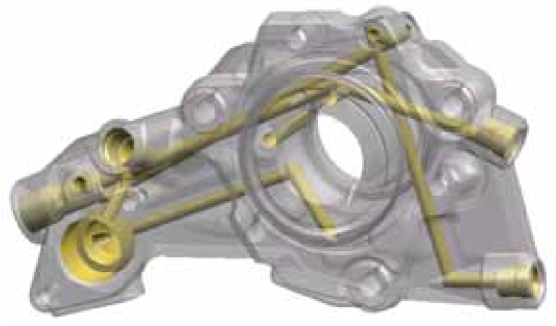

Figure 2. Original diesel front plate design, grey areas show main body casting, yellow areas are machined diesel pathways

The original design is currently manufactured using a combination of gravity die-casting and machining operations. These production operations will be dealt with more completely in section 4.2.1. There are a number of issues with the front-plate which will be looked into during the design for RM study, these are:

1. Flow channel design
2. Excess material and weight

The design exercise has been carried out with DDS designers in order to produce an “optimised” structure capable of carrying out the necessary tasks. In addition the original and optimised components have been used for further study of manufacturing using metallic RM systems as outlined in section 3.2.

3.2 FSWP2 Benchmarking of RM Processes

FSWP2 assesses the difference between processing the a component using RM technology and traditional methods of production in terms of energy efficiency, water, solid and gaseous waste produced. The methodology for the manufacture phase of ATKINS has been developed to compare and contrast conventional manufacturing systems with RM. Where possible data on the 5 BREW metrics has been gathered from project partners on traditional and RM systems to allow for a comparison.

3.2.1 Metallic

The case study component, as shown in Figure 2, has been used as an example for comparison of the traditional manufacturing route shown in 4.2.1. This is in comparison to the possible RM manufacturing methods that will be developed during the full project stage. In order to make a comparison with current manufacturing technology, the Delphi diesel front-plate has been manufactured by one of the project partners (MCP) and the energy usage monitored during manufacture of firstly the original design and secondly the optimised component.

3.2.2 Polymeric

Studies on polymeric RM have been carried out with the component shown in Figure 3.

Figure 3. Computer Aided Design (CAD) image of injection moulded clip

This clip design has been manufactured using both traditional forming techniques, i.e. injection moulding (information provided by MCP) and has been compared with laser sintering RM technology provided by Bentley. The energy usage of the two systems has been compared as has waste material production.

3.3 FSWP3 Distributed Manufacturing and Logistics

FSWP3 has investigated the possibility of using RM as a method for radically changing the supply chain for a product/component and in doing so changing the logistics requirements for that part. By doing this the number of “part miles” could be reduced, particularly if a distributed manufacturing stance can be enabled by the project partners. The use of RM has the ability to radically change the way that the supply and logistics chains are organised. Working with Perkins, an example supply chain has been studied to ascertain how a typical supply chain operates and where the carbon footprint can be improved. The results of the study can be found in section 4.3.

4 Results and Discussion

4.1 FSWP1 Design for Low Carbon

A 3D CAD image of the original front-plate design can be seen in Figure 2. The design flexibility of RM has shown great promise for developing optimal designs in the past[32]. Exploiting this design freedom is of critical importance when attempting to optimise components for different functions.

Following a re-design of the Front-plate carried out in conjunction with DDS a new design has been realised incorporating a number of features that can only be realised with RM systems. The design process has been evolutionary in nature and the internal channel changes can be seen in Figure 4.

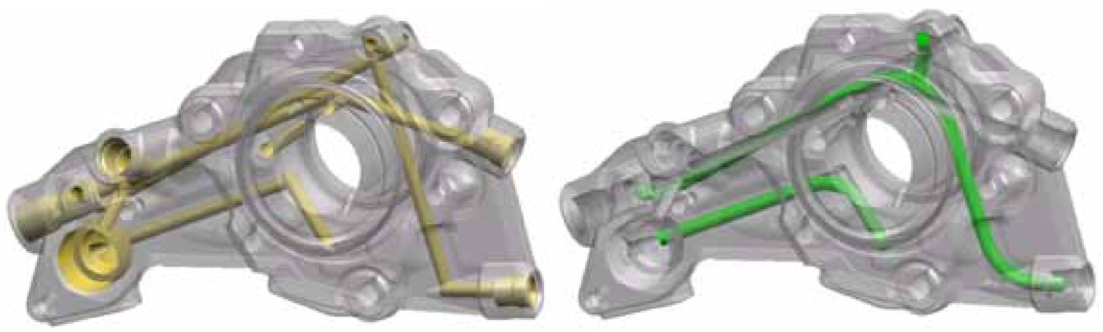

Figure 4. Evolution from traditional design (left) and RM design (right)

The evolution from the traditional design to that enabled through RM is only possible as the internal channels are able to be produced in-situ during Rapid Manufacture. In comparison, the channels produced in the traditional design are made through drilling straight holes in the casting. In addition to the drilling operations, these holes need to be blocked to prevent leakages of diesel in the pump. Producing the holes directly into the part the production of burrs and swarf is negated and so the machining and cleaning operations are removed.

With the production of flow channels directly into the component it was then possible to remove extraneous material from the original casting. This results in reduced material usage and a reduced envelope for the component within the engine bay. A comparative image is shown in Figure 5.

Figure 5. Comparative image of RM design (blue) overlaid on the original design (grey)

The improved design is shown in Figure 6 and incorporates weight reduction and improved flow characteristics at the design’s core.

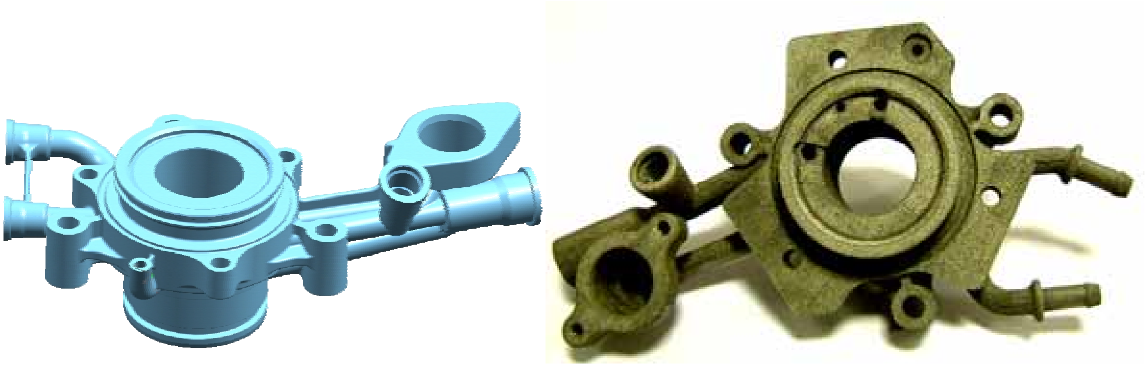

Figure 6. Re-designed front-plate component (left) and an example manufactured using SLM (right)

In comparison with the original front plate it can be seen that the RM component is of a radically different geometry whilst incorporating the features required to conform with the existing fixtures and components that it needs to connect to.

The differences are borne out of the fact that the component has been designed around the flow channels rather than adding the flow channels as a later process. The benefit this has is that no swarf or burrs are created internally, requiring Electro-Chemical Machining, and, unlike the original, the channels do not need sealing with additional material (such as ball bearings). Therefore, the channels have a consistent flow architecture and the extraneous material is not a consideration.

4.2 FSWP2 Benchmarking of RM Processes

4.2.1 Metal traditional manufacturing route

The original front-plate design is currently manufactured as shown in Figure 7:

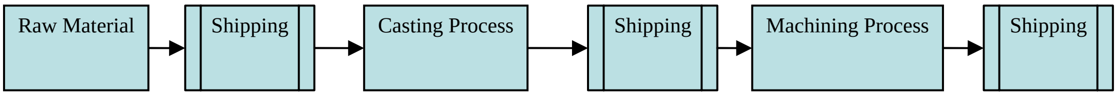

Figure 7. Manufacturing processes for original front-plate design.

Breaking the manufacturing aspects of the front-plate down to their individual components allows the different energy and waste components to be identified. A breakdown of the casting process is shown Figure 8.

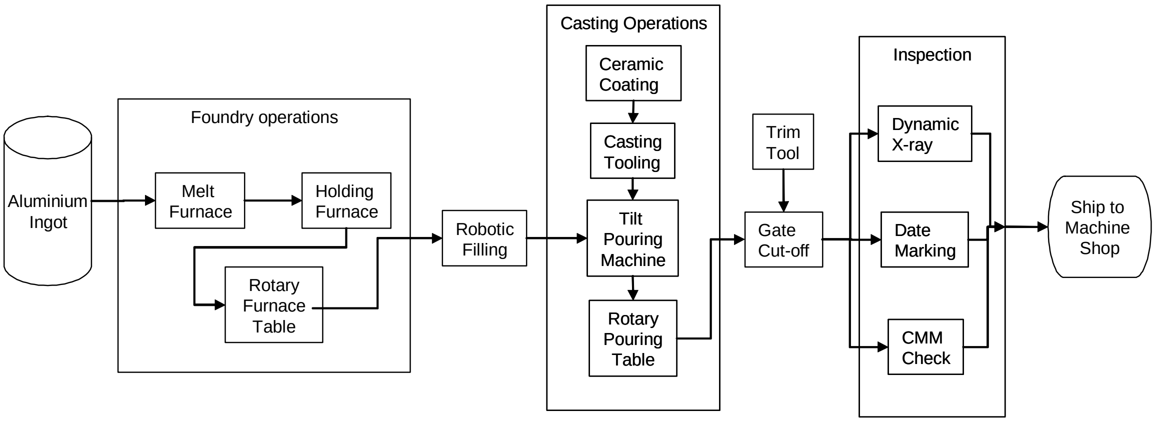

Figure 8. Breakdown of the casting process.

Analysing the casting process in terms of the BREW metrics the environmental effects of the different aspects of manufacture, using data from the literature and Delphi, it is possible to show where the process in terms of energy consumption water usage etc.

Process	Energy Use kg CO_2e per component	Water Usage (kg per component)	Landfill Waste (kg)	Virgin Material Use (kg per component)	Hazardous Waste (kg per component)
Casting	1.9	0	N/a	2	N/a

Table 6. Environmental impact metrics for casting process

For this component the casting required further machining in order to add in the necessary internal channels and external features (Figure 9).

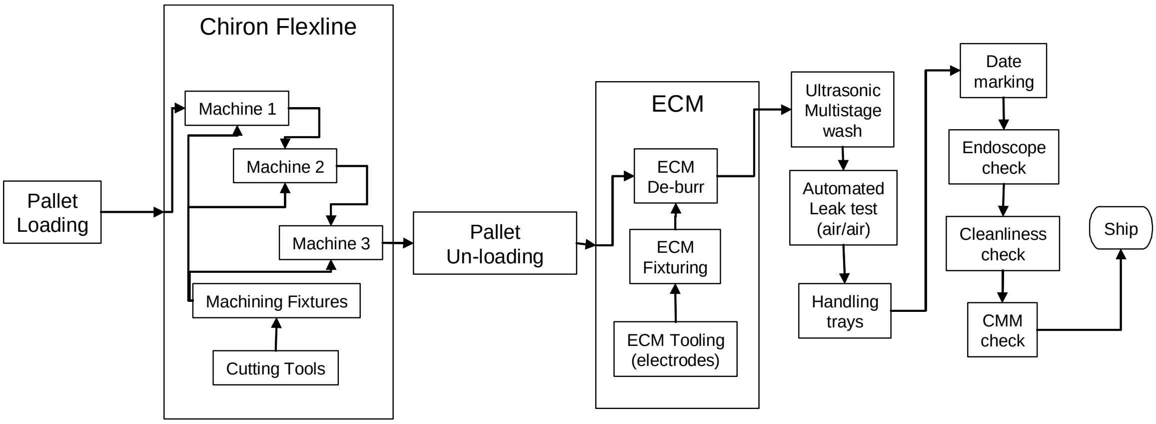

Figure 9. Breakdown of the machining process.

The machining process incorporates several aspects in addition to the machining operation carried out by the Chiron Flex-line equipment (£3 million per module). Electro-Chemical Machining (ECM) was required to remove burring on internal channels. Again, a review of the BREW metrics for the process has been carried out and can be seen in Table 7, data for the ECM process was not available at the time of writing.

Process	**Energy Use kgCO_2e per component**	**Water Usage (kg per component)**	**Landfill Waste (kg per component)**	**Virgin Material Use (kg per component)**	**Hazardous Waste (kg per component)**
Flexline	2.4	0.08	1.512 (waste can be recycled)	2 (from casting)	0.0064[ii]
ECM			Not Available		
Clean	N/a	0.15	N/a	N/a	N/a

Table 7. Environmental impact metrics of machining process

Using RM for this component radically reduces the number of manufacturing operations due to the net shape nature of the process. The traditional casting and machining route can be reduced to the following:

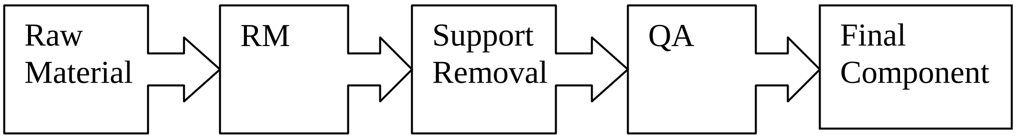

Figure 10. Process flow for RM of Diesel Front-plate.

[ii] Coolant lubricants at 8% concentration[9]

The RM system will directly convert the powdered raw material into the finished component and support structures will need to be removed as necessary. Once built it is envisaged that the component will go through an identical QA procedure and so this can be ignored during the comparison. The ECM stage is removed as no machining is necessary on the internals of the component. The reuse rate for unused powder is approximately 96% (including support structures). For the original designed component Table 8 illustrates the BREW factors.

Process	Energy Use $kgCO_2e$ per component	Water Usage (kg per component)	Landfill Waste (kg per component)	Virgin Material Use (kg per component)	Hazardous Waste (kg per component)
RM	13.15	0	0	0.65	0
Support Removal	N/a	0	0	0.026	0

Table 8. BREW factors for RM of Original Delphi Diesel Front-plate

The optimal design (Figure 6) differs in the amount of virgin material used and the energy use (due to the change in geometry) during the manufacturing phase of the component. This is discussed in section 4.4.2.

4.3 FSWP3 Distributed Manufacturing and Logistics

The Irlam branch of the Perkins supply chain has been analysed as a typical logistics operation to highlight possible changes to the supply chain operation. Irlam is an 1700 m^2 warehouse located in Cheshire that receives deliveries of:

- Cylinder heads
- Engine blocks
- Pumps
- Complete engines
- Other engine parts

Supplier deliveries are made between 7 am and 3 pm, while Perkins deliver to the site at 9 pm. The average distance travelled to and from the site is 520 km per delivery with approximately 200 deliveries per week from 13.5 m long trucks. These products delivered to the Irlam branch are packaged in a variety of metal, wooden and cardboard materials, with metal stillages being returned to the supplier. Wood is the largest single waste stream at the plant at 62 tonnes p.a. General waste from the warehousing operation accounts for 72 kg per week or 3.8 tonnes p.a. The total costs of waste management and disposal account for approximately £12,000 p.a. Additionally, the stock turnover rate is on average 2.03 stock turns p.a. For the products delivered to Irlam their final destinations are global including: Far East, South Africa, the Americas and Europe.

4.4 Major Environmental Impact

The major environmental impacts that were envisaged for ATKINS at start of the feasibility study were centred around improvements to design and distribution elements that were enabled by the RM process. Using the case studies as indicators, the following sections will provide an overview in terms of the environmental and social benefits resulting from the use of RM as a manufacturing method. These environmental effects will be connected to possible economic benefits resulting from the use of RM.

4.4.1 FSWP1 Design for Low Carbon

The resulting new design has consequences not only in the amount of material used during its construction but also on the amount of energy required during its use phase. Reducing the weight of individual components can be seen as having a greater effect on the fuel consumption of vehicles during their lifetimes. Simply comparing the two designs in terms of their volume (Table 9) shows that a reduction of almost 40% can be gained just through the use of additive design practises directly contributing to BREW 4.

Design	Volume of part (m^3)	Volume Fraction (%)	Part Weight Aluminium (kg)
Optimised	1.51×10^{-4}	63	0.418
Original	2.39×10^{-4}	100	0.65

Table 9. Comparison of optimised RM design and traditional design on part volume and weight

This reduction may be able to be improved further if surrounding subsystems can be relocated and brought closer to the front-plate, therefore further reducing the size of the front-plate.

4.4.2 FSWP2 Benchmarking of RM Processes - Metallic

A comparison of traditional and RM manufacturing techniques have the following impact on the environment in terms of the BREW metrics.

Original Design	Energy Use kg CO_2e per component	Water Usage (kg per component)	Landfill Waste (kg)	Virgin Material Use (kg per component)	Hazardous Waste (kg per component)
Traditional	4.3	0.23	0	2	0.0064
RM (SLM)	13.15	0	0	0.67	0
Difference	8.85	-0.23	0	-1.33	-0.0064
Optimal Design					
RM (SLM)	8.72	0	0	0.43	0
Difference	4.42	-0.23	0	-1.57	-0.0064

Table 10. BREW metric changes for traditional versus RM manufacturing of original and optimal Front-plate design. Environmental benefits highlighted in red.

Table 10 shows where the current differences occur for the data gathered for the traditional and RM systems manufacturing the original design, and, the RM system manufacturing the optimal design. The RM system wins, environmentally, in the water usage, hazardous waste and virgin materials categories, but falls down in the use of energy per component. Taking data for the RM manufactured optimal design and the traditionally manufactured original design, the best case scenario exists for RM. For each component manufactured, current RM technology will emit 4.42 kg more CO_2e but reduce water consumption by 0.23 kg, virgin material use by 1.57 kg and hazardous material consumption by 0.0064 kg. However, for the traditional manufacturing route it is unrealistic to assume a single component volume, as tooling investments (in this case €250,000) etc. have been made on an assumed given unit volume p.a. whereas RM requires no tooling.

If this is scaled to typical front-plate production quantities of 2,000 and 100,000 units p.a. (depending on application), the following environmental impacts are ascertained for the traditional process and original design vs. RM of the optimised design. These differences are shown in Table 11.

Volume	Energy Use during manufacture (kg CO_2e)	Water Usage (kg)	Landfill Waste (kg)	Virgin Material Displacement (kg)	Hazardous Waste (kg)
1	4.42	-0.23	N/a	-1.57	-0.0064
2000	8,840	-460	N/a	-3,140	-13
100000	442,000	-23,000	N/a	-157,000	-640

Table 11. BREW metric differences for traditional process/original design vs. RM / optimised design. Figures in red outline environmental benefit.

The RM process as it stands is more energy intensive than the traditional manufacturing process, however, it does save on water use, virgin material and hazardous waste.

The "buy-to-drive" ratio of 2:0.7 for the traditional process means that there is a significant virgin material saving, which has a knock-on effect on the total energy bill of producing the component. As less material is necessary for RM, less energy is needed to convert raw material to material for processing. Approximately 14 kWh of energy are needed to produce 1 kg of primary Aluminium[33]. Thus the energy needed to convert the extra material to Ingot form for traditional manufacture of the Front-plate equates to **945 tCO_2e, over double the extra energy required to produce the components via RM**. Though there will be extra energy in converting the pure Aluminium into powder form this additional energy cost has been shown by Morrow et al. to be negligible. Table 12 shows the overall benefits from taking an holistic RM approach to manufacturing the optimal front-plate

Production Volume	Energy Use during manufacture (tCO_2e)	Water Usage (tonnes)	Landfill Waste (tonnes)	Virgin Material Displacement (tonnes)	Hazardous Waste (tonnes)
100,000	503	23	N/a	157	0.64

Table 12. BREW savings for RM of the optimal front-plate as compared to the traditional manufacturing of the original design, for a p.a. volume of 100,000

One of the important differences between metallic and polymeric RM systems, that will be come apparent, is that the metallic RM under analysis here is able to reuse virtually all materials (96%) that are not converted into the component or support structure. The reduction in part weight and size has significant impacts for 2 BREW metrics, namely energy usage and virgin material displacement. Additionally, due to the nature of RM, no water or CL are needed during the manufacturing cycle. The only waste is support structures used to fix the component to a base plate. This reduction in raw material usage has a knock-on effect during the product use-phase of the product lifecycle (section 4.4.5). The ability to reduce the amount of material in the component has the obvious effect of reducing the weight of the component, having a direct benefit for many applications, particularly the transport sector.

Additionally, end of life issues for metallic RM are minimal as the materials are those common to metallic recycling. Indeed if assemblies and products can be consolidated during the design phase, as shown by Hopkinson et al., RM may be able to reduce this burden further, reducing the lifecycle impact of the component.

4.4.3 FSWP2 Benchmarking of RM Processes - Polymeric

Comparison of the polymer systems has taken place between Injection Moulding (IM) carried out at MCP and LS carried out at Bentley. Using the component design shown in Figure 3, the BREW metrics have been analysed. It must be stressed that RM systems based on LS are not able to process a wide variety of materials. The RM system at Bentley has produced parts using glass-filled Nylon 12, whereas the IM machine has produced components in PC-ABS. The design has not been modified in anyway for RM and as such the comparison is a direct comparison between the two manufacturing techniques.

Using data from partners and the literature a comparison of the two methods of manufacture can be made, shown in Table 13.

Original Design	Energy Use kg CO_2e per component	Water Usage (kg per component)	Landfill Waste (kg per component)	Virgin Material Use (kg per component)	Hazardous Waste (kg per component)
Injection Moulding	0.003	N/a	0.001	0.010	N/a
Laser Sintering	0.084	0	0.065	0.006	0
Difference	0.081	N/a	0.064	-0.004	N/a

Table 13. Polymer manufacturing comparison

Firstly, landfill waste has been monitored for comparison. Injection moulding waste is evident in the sprues and excess material required to mould the component, with a single mould cavity this is a relatively small quantity that can be recycled. However, the RM system requires excess material to support the components during manufacture. Using a build strategy as shown in Figure 11, it can be seen that there is a lot of excess space surrounding the planned components, this space needs to be filled with material to support these components.

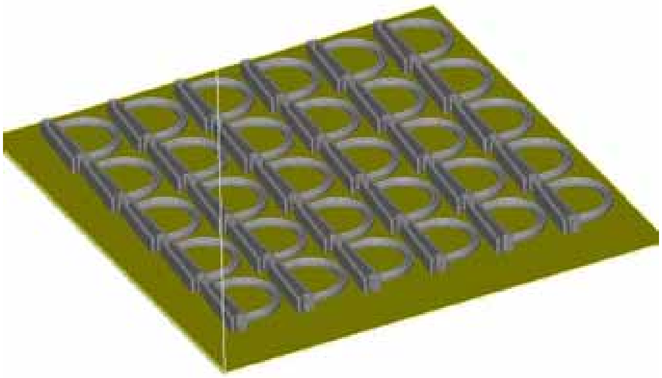

Figure 11. Build strategy for maximum components per build

Luo et al have commented that laser sintering has a material utilisation rate (MUR) of almost 100%, whilst this is true for the product, there is excess material needed in the build chamber, which is significant. Some of this excess material can be recycled and Bentley currently use 40% of this material in subsequent builds; meaning that 60% goes to landfill. For a single layer of 30 components (6 g of material each), as shown in Figure 11, the waste per component is 65 g per component, totalling 1.97 kg.

The main reason for this amount of waste, when compared to metallic RM, is the thermal cycle which the polymer powder undergoes during the manufacturing cycle. The whole bed of powdered polymer is heated to below melting point and then melted using a laser beam. As such, on cooling and removal the excess polymer material has changed in terms of it's material properties, and so only a limited amount can be re-used to remain part integrity. It is possible to reduce this weight of excess material, through more efficient packing of the build volume, however, a minimum part separation will always exist resulting in some waste powder.

4.4.4 FSWP3 Distributed Manufacturing and Logistics

The distribution element of the study has focused on a Perkins Engines logistics warehouse (Irlam) that houses engines and components. One of the often quoted benefits of RM is that it will be possible to change the supply chain radically, effectively moving to a localised supply chain that receives digital data via the Internet and produces components on demand for the local users. Walter et al.[18] have shown this concept as a method for reducing aircraft down time and reducing inventory (and therefore working capital) at locations spread across the globe.

The work undertaken at Perkins has identified the following which may be affected through the use of RM.

Distribution	Energy Use tCO_2e p.a.	Water Usage (tonnes p.a.)	Landfill Waste (tonnes p.a.)	Virgin Material Use (tonnes p.a.)	Hazardous Waste (tonnes p.a.)
Irlam Warehouse	7240	N/a	66	N/a	N/a

Table 14. BREW metrics for typical distribution chain, data supplied by Perkins Engines; all data p.a..

Energy use is the amount of energy to get the parts to and from the warehouse, 200 deliveries per week at an average distance travelled of 520 km, equates to 5.2 million km p.a. travelled. At an average fuel consumption[34] of 51 l per 100 km, 2.65 million litres of Derv are consumed moving components to and from the facility, or 7,240 tCO_2e.

4.4.5 Wider product lifecycle benefits

The component used for metallic RM was a vehicle component from DDS. One of the market sectors where RM could have significant benefits both in environmental savings and economics is that of Transport. Recent work by Helms and Lambrecht[35] has attempted to define the increases in fuel efficiency through the light-weighting of various types of vehicle. Helms and Lambrecht have concluded that weight is a significant factor for reducing fuel, and therefore energy consumption over the lifetime of the vehicle. Their work used an arbitrary 100 kg reduction in weight and analysed the potential savings during vehicle use. Energy used during manufacture was not taken into account.

Vehicle Type	Specific end energy savings per (100 km * 100 kg)	Use phase performance (million km)	Use phase end energy savings per 100 kg	CO_2e saving per vehicle
Passenger car (gasoline)	11.3 MJ	0.2	23 GJ	1.53 kt
Passenger car (diesel)	10.7 MJ	0.2	21 GJ	1.46 kt
Articulated truck	2.1 MJ	1.2	26 GJ	1.8 kt

Vehicle Type	Annual end energy savings per 100 kg	Use phase (years)	Use phase end energy savings per 100 kg	CO_2e saving per vehicle
Short distance aircraft	500 GJ	30	15,000 GJ	1 Mt
Long distance aircraft	667 GJ	30	20,000 GJ	1.33 Mt

Table 15. Estimated energy savings related to 100 kg weight saving per vehicle over normal lifetime. Modified from Helms and Lambrecht

These energy savings also translate into cost savings over the useful lifetime of the vehicle. For example if a diesel car is able to save 21 GJ of fuel this translates to a physical saving of 577 litres of diesel at a cost of £0.95 per litre[36] a saving of just under £550 pounds will result. For aircraft the energy saving is even more significant, ignoring improvements in energy technology that may come from design improvements available from RM for long distance aircraft, a saving of 20,000 GJ is possible or 4.5 million litres. This results in an operational cost saving of $2.5 million at today's Jet fuel prices ($91 per barrel[37]) over the lifetime of the aircraft. As an example, Virgin Atlantic currently operate 30 aircraft in long-haul operations, translating these savings across the long-haul sector at Virgin would save them $2.5 million p.a.

4.5 Supply chain restructuring

The opportunities for restructuring the supply chain with RM are massive and could take on a global significance. For the following reasons:

- **Dematerialisation of the supply chain –** RM requires suitable 3D CAD data from which to produce the part or product. Consequences for the supply chain will be to *dematerialise* the supply chain through distribution, globally, without the necessity to send physical objects, these parts or products could then be *re-materialised* with appropriate RM equipment.
- **Just-In-Time –** With the 3D CAD data and raw material to produce a component, the application of RM in the manufacturing environment will result in a reduction of material distribution and stock holding or warehousing costs for work in progress (WIP). The ability to amalgamate RM with Internet technology and other manufacturing systems (MRP *etc.*) will lead to JIT *manufacture* at the factory, rather than the traditional concept of JIT *delivery* to the firm. Thus reducing warehousing and logistics costs in addition to fuel and energy savings.

- **Reduced set up, changeover time and number of assemblies** - It must be stressed that the production of parts through RM will change the manufacturing paradigm from that of skilled labour operating machinery and forming a large portion of part cost, to one where the burden of cost is transferred to the technology or specifically the RM machine and materials. A further driver for the reduction of costs is in the product design. For example, RM processes may make traditional designs obsolete, by reducing the need for assemblies and thus the production process may provide cost savings for parts and components. As RM requires no tooling changes to produce different parts or products, time that is traditionally lost to these factors will be reduced.
- **Elimination of Waste -** A principle driver for Lean production is to reduce waste wherever possible in the supply chain. The effect that RM will have on this area will be especially significant, if arguments about dematerialised supply chain are taken into account. Integration with Internet technology will result in the fast exchange of data between designers and manufacturers, where in the case of RM, this data can be sent directly to the RM system for build.

The potential for supply chain restructuring from the ATKINS project are significant. The premise set out at the beginning of the feasibility study is that ATKINS is able to affect the Design, Manufacturing and Distribution of components and products. The work shown in this report have certainly shown that there is scope for RM as an enabler for ZEE, however, there are many fundamental aspects of the design and manufacturing process, and the organisation of the supply chain that require significant work for this to be fulfilled.

Current 3D CAD systems and analysis software are not able to cope with the complexity of design afforded by RM, thus limit the scope for manufacturing truly optimal components. The metallic RM systems, although able to process real metallic components with material properties close to those of wrought materials, are unqualified for many applications, which has led to mistrust in the design and manufacture communities. The potential of the manufacturing complexity of RM which lend themselves to improved and optimised eco-design have been demonstrated, but possibly the biggest potential lies in re-structuring the supply chain. Studies have shown that the economics of RM do not lie in labour, but in the technology. This move of costs away from the labour content of a product challenges the existing trend of globalisation as the driver to out-source (low wages and therefore low cost) is eroded.

RM is capable of radically altering the supply chain for many manufacturing industries (not just the transport sector) allowing distributed manufacture at the point of need, therefore reducing logistics costs and enabling local supply chains to deliver to local manufacturers.

4.6 Technological Innovation

All previous studies on the environmental effects of additive manufacturing have been on the use of RP or Rapid Tooling (production of tooling using additive methods). This is significant as it goes against the fundamental idea of ATKINS. Studies on RP have monitored the energy usage and waste production for RP parts and components, not for components that will be used as or on a product. Thus the components built by these RP systems have not been designed for the process but more likely designed for a traditional manufacturing process such as injection moulding or casting. This means that the design intent for the component cannot take advantage of the additive manufacturing process and utilise the design freedoms that enable optimal designs.

If it were possible to build components using RM systems, in both metallic and polymeric materials, then the design opportunities would enable lower weight and high performance products to be manufactured. This will have a knock-on effect to the use-phase of the product lifecycle enabling greater efficiency and, if the transport sector were targeted as a market, it could have great gains in terms on fuel efficiency and consequently emissions. Couple these advantages with the ability to *manufacture* JIT rather than *deliver* JIT, and send part data digitally to the point of manufacture and assembly then great emissions savings may be made when developing supply chains and logistics plans.

The work of this Feasibility Study has informed that the full ATKINS project should focus on the burgeoning metallic RM systems. Recent work has led to a number of systems able to process a variety of metallic powders. The technical issues surrounding these systems are akin to those producing polymeric components, in that the systems have not been produced with “manufacturing in mind” but as prototyping machinery and thus they suffer from issues of material qualification, surface finish and accuracy in addition to inefficiencies during build. However, they have a number of advantages in that the metallic materials are accepted metal alloys, and all powder not used during manufacture can be recycled, unlike polymer systems. ATKINS will look at all of these factors as a whole in order to bring a holistic solution to the manufacturing community that not only offers environmental benefits but economic ones too.

5 Conclusions and recommendations

The “ATKINS” project was commissioned on the 31st April 2007 for a period of 5 months to investigate the potential contribution of Rapid Manufacturing (RM) as a method of reducing the environmental effects of manufacturing enterprises. ATKINS was very favourably received at the feasibility submission stage:

“The panel was very supportive of this proposal because it is well aligned with the ZEE objectives and you have an appropriate consortium to deliver the project at both the feasibility and full stages.”

This report has shown the significant potential of RM as an enabler for the Technology Programme call: “Moving Towards a Zero Emission Economy” or ZEE. The scope of the feasibility study was to outline where the technology (RM) has a *capability* to affect business processes in terms of *sustainability* and *competitive advantage*.

Emissions from manufacturing and transportation are a major contributor to GHG emissions and thus global warming on both a global and national level. The use of RM as a method for reducing the overall emissions in manufacturing, particularly for transport markets, directly contribute to the ideal of “*producing more with fewer natural resources and pollution”*[38] Though for the un-optimised systems the energy usage during the manufacturing stage may be higher than the energy usage of conventional manufacturing techniques, when the ancillary emission and waste are taken into account the arguments against RM begin to stack up. This is especially true when a whole lifecycle approach for a given product is taken. It has been shown that for metallic systems the production of raw material (in this case tool steel) for RM, if done directly, has a lower energy consumption than producing plate steel for machining. Additionally, taking into account the buy-to-fly ratios that are common in the aerospace industry (i.e.10:1/15:1) for every kilogram of component that is produced 10x this goes for recycling, which is energy intensive.

The work presented in this feasibility report has shown that there is indeed promise for RM to radically alter the way components are produced in order to reduce the environmental burden of existing manufacturing operations. This has been especially significant for the metallic component analysed during the study. For polymeric RM, the amount of waste and inability to produce from “traditional” engineering polymers means that a great deal of fundamental polymer research is necessary to consider these systems for ZEE. The metallic systems however, are much closer in terms of mechanical properties, but less engineered in terms of the system maturity. It is therefore the recommendation of this report that the full stage ATKINS proposal concentrates on the development of a fully validated *metallic* production cell, that is optimised for energy usage, long term material properties and acts as a demonstrator for the project partners as to the capabilities of the system, design and supply chain restructuring. The supply chain element is of particular importance as there is no current RM supply chain. Any company using these types of technology has, normally, bought systems in-house.

In terms of market sector, the first focus should be both land and air transportation. Here the design element of ATKINS can make real benefits into the carbon footprint of the product. In the UK 2.3 million new passenger cars were sold in 2006, using the figures shown in Table 15, the CO_2e saving from those vehicles would equate to approximately 3 GtCO_2e over their lifetime, for just a 100kg weight saving per vehicle. These figures may seem excessive, but these products have considerable energy usages during their lifetime and better design, facilitated by more innovative production methods will have significant impact due to the volumes of these products sold in the UK.

These arguments mean that the ATKINS feasibility study directly impacts on issues raised in the Low Carbon transport Innovation Strategy, published by the Department for Transport in May 2007. The possible applications and improvements due to metallic RM will directly affect CO_2e emissions in the ground, air and even water transport[5, 35] sectors.

The possible savings in energy consumption will highlight RM as a technology able to radically change the manufacturing sector. RM is a re-configurable and adaptable technology and it is envisaged that through the full project ATKINS will initiate the development of a new, UK based, manufacturing community in a number of different market sectors.

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