25TH INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
7-8 SEPTEMBER 2023, ELISAVA UNIVERSITY SCHOOL OF DESIGN AND ENGINEERING, BARCELONA, SPAIN

AN ADVANCED MANUFACTURING SUPPORTED SUPPLY CHAIN – EDUCATIONAL CASE STUDIES

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ABSTRACT

This paper details the design process and analysis undertaken within the Royal National Lifeboat Institution (RNLI) to positively disrupt the supply chain using advanced manufacturing technologies, and then how this information has been utilised and adapted for teaching to product design and engineering students at Bournemouth University (BU) to consider in their future design work. Analysing engineering components alongside their supply chain data led to creating case studies which detail the benefits Additive Manufacturing (AM) could offer the RNLI. The aim of this research was to identify specific areas where additive manufacturing could be implemented into the engineering industry to have positive outcomes, such as cost and lead time savings, and then disseminate this real world manufacturing knowledge to design and engineering students. It was found that through redesigning two lifeboat components that reduced lead times, reduced cost, and reduced component weights could be achieved. These real world findings then led to informative case studies being developed to aid in the teaching of designing for additive manufacturing for product design students at Bournemouth University.

Keywords: Supply chain, additive manufacturing, advanced manufacturing, 3D printing, design, higher education

1 INTRODUCTION

The goal of traditional supply chain spare parts management is to maintain a minimum level of spare parts inventory whilst still being able to fulfil demand and maintain customer satisfaction. Optimising product flow and stock levels generally require transporting spare parts to the point of use from a centralised storage location [1]. While moving from a decentralised to a centralised network can lower costs and improve service performance it will have a negative impact on the environment due to the increase in transportation needs [2]. It has been recognised that Additive Manufacturing (AM) technologies have the potential to positively disrupt the supply chain by reducing the requirement to hold and transport stock, produce cost and lead time savings, while also guarding against supply chain disruption.

The Royal National Lifeboat Institution (RNLI) is a UK charity that saves lives at sea. Its headquarters is based in Poole, Dorset, UK and the institution has 238 lifeboat stations around the UK which currently require the delivery of stock on a regular basis. It opened its All-weather Lifeboat Centre (ALC) in 2015 where it now manufactures and maintains its fleet of 431 lifeboats. It was found that the current inventory level held by the RNLI at its headquarters has a value in excess of £20million, an average age of 13.85 years and a demand ratio of 1.84 [1]. This means that the RNLI holds nearly double the amount of stock, which is demanded each year, and on average a component ends up costing the RNLI 346% of the initial part cost once used. It was established that the RNLI holds excessive amounts of inventory because of a 'just in case' reasoning, which leads to expensive storage, transport and disposal costs, should any components become obsolete. Therefore, AM was investigated as a manufacturing technique for the RNLI in order to reduce the requirement to hold, move and dispose of the current costly and excessive inventory. The RNLI stated in their 2018 Annual Report and Accounts that this type of manufacturing would have a positive impact on their sustainability, in both financial and environmental terms [3]. The RNLI has committed to eliminating or reducing their negative impacts on the environment and to becoming a low-carbon, zero-waste-to-landfill and climate-resilient organisation in the future [4].

A project, providing academics and students with the opportunity to collaborate with the RNLI, was funded by Bournemouth University's (BU) allocation of Higher Education Innovation Funding (HEIF). HEIF is provided to support knowledge exchange between higher education providers and the wider world that benefits society and the economy. Key objectives of this project were to work with the RNLI to investigate the potential impact of introducing AM on their business while providing opportunities to enhance student learning. This article presents results of the findings of the project undertaken with the RNLI and then details how this information has been utilised and adapted for teaching to product design and engineering students.

2 RESEARCH METHOD

2.1 Literature Review

Literature surrounding the subject of additive manufacturing, and how it could positively disrupt supply chains across different business sectors analyses strategic investments in AM for the maritime industry, how it could be used and adopted, and is developing a mind-set for which organisations should follow to adopt to the technology [5], [6]. However, the literature also suggests that in order for the maritime industry to move forward with AM and the benefits it has to offer, real maritime case studies and experiences need to be generated [5], [6]. Current literature informed the research project as it enabled insight into how the maritime industry are adopting these technologies in different ways, further benefits that it has to offer the industry, and how this could potentially be applied to the RNLI.

2.2 Primary Research and Analysis

Supply chain data from cradle to grave was collected via meetings with key stakeholders within the organisation. The key stakeholders included the Procurement Manager, Warehouse Manager, Innovation Manager, Engineers, and Senior Engineers. A key starting point of the project involved working with a Senior Category Manager within the supply chain to understand where the research should focus to achieve strong outcomes. The RNLI categorises stock dependent on the speed that it moves through stores. From category 'A' being fast moving stock, through to category 'C' being slow moving stock. Through investigations with key stakeholders of the project it was decided that category 'C' components, and items with long lead times, could most benefit from the implementation of AM. These parameters were selected as these parts cause problems for the RNLI supply chain in terms of inventory management and unnecessary costs (high storage costs). Analysis was conducted on component data regarding lead times, costs, materials, and AM suitability. This led to several components being selected as suitable for this research study to show the benefits AM could offer the RNLI.

Two variations of AM were explored in the research. Both were different types of composite 3D printing as this would allow the RNLI to produce end use components fit for purpose when out at sea. Although both offer composite 3D printing, they do so in different ways. These are chopped strand composite printing, and continuous strand composite printing. Stratasys (Minnesota, US) offer a material called Nylon12CF, which is capable of being printed on their Fortus production systems. Nylon12CF is a Fused Deposition Modelling (FDM), carbon fibre (chopped strand) reinforced thermoplastic. The material properties of Nylon12CF include high strength-to-weight ratio as well as high tensile strength [7]. Markforged (Massachusetts, US) offer 3D printing in a combination of Onyx and continuous strands of reinforcing fibres. Onyx is Markforged nylon thermoplastic which is infused with chopped carbon fibre. The continuous reinforcing fibres then include; carbon fibre, fibreglass, high strength- high-temperature fibreglass and Kevlar. Markforged claim that Onyx material reinforced with carbon fibre is strong enough to replace aluminium at half the weight and can be used when superior stiffness and minimal deflection is required [8].

3 RESULTS AND DISCUSSION

The analysis of components, from a supply chain perspective, gave a number of components that would be suitable to perform in-depth research upon to demonstrate the advantages AM could offer the RNLI's supply chain. With supply chain (reduced lead time, reduced cost) and engineering benefits (weight reduction, corrosion resistance) in mind the list of suitable components was narrowed down to two. These specific components were chosen as they both sat in category C stock, meaning they were slow to move through the warehouse, but because of their long lead times the RNLI always had to keep several of them in stock ‘just in case’ they were urgently needed. These two specific components are the ‘Mast Latch Handle’ and the ‘Sea Water Inlet Strainer’.

3.1 Mast Latch Handle

The mast latch handle is a part used on a Shannon lifeboat to lock the mast into position. The part is currently made from aluminium and is manufactured via a traditional subtractive technique (CNC mill) from stock material. The mass of this part is 0.182kg, its lead time is 28 days, and its cost is £221.91. Both variations of composite AM from Stratasys and Markforged were investigated in this case study. Machine information, printing parameters, and final component information can be found in Table 1:

Table 1. AM Mast Latch Handle Information

	Stratasys Component	**Markforged Component**
Part Fill	100% Solid Nylon12CF	Triangular Fill 37% - 13cm^3 Carbon Fibre Reinforcement
Print Time (hours)	1.48	7.20
Component Cost (£)	21.49	36.65
Component Mass (kg)	0.073	0.048
Parts per build plate	7 max	2 max (Mark Two)/ 4 max (X7)
Machine Cost (£)	58,000	11,995 (Mark Two)/ 52,672 (X7)

This data shows the benefits the additively manufactured composite components offer over the current aluminium part from a supply chain perspective in lead time, part cost, and mass reduction. To benefit from the component cost and print time provided above, purchasing a machine to have on site is required. The Stratasys Fortus 380mc Carbon Fibre edition is quoted as £58,800 (September 2019), the Markforged Mark Two desktop is quoted as £11,995 (September 2019), and the Markforged X7 is quoted as £52,672 (September 2019). As this is an engineering component it was vital to prove that the additively manufactured composite component would be able to perform comparatively to the aluminium one in service. After analysing how this component is used it was vital to conduct testing on the part which mimics what it is exposed to in real world situations. The main test conducted was a force/deflection test to analyse stiffness. This test was used to compare deflection that would occur when subjected to real world loading. This test was carried out on the aluminium part, the Stratasys Nylon12CF part and the Markforged part containing 13cm^3 of reinforcement. The force/deflection setup and test results can be seen in Figure 1.

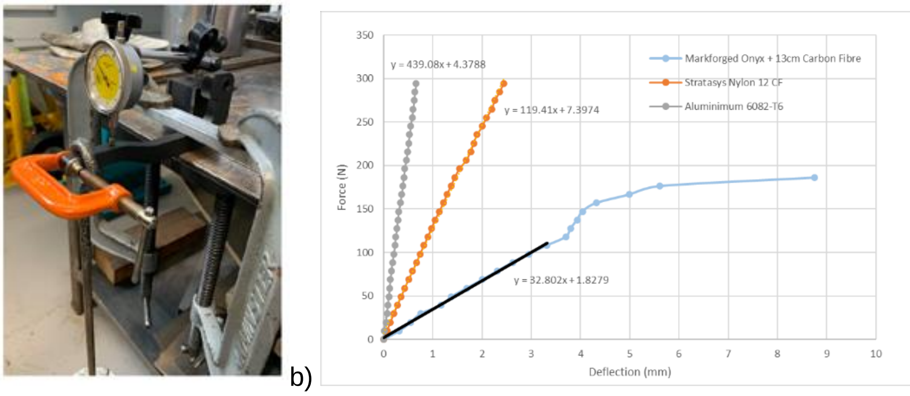
a)  b)

Figure 1. Force/Deflection a) Test Set Up and b) Test Results

The results show the Markforged component with 13x10^{-6}m^3 of carbon fibre reinforcement failed at 196.2N (20kg). The aluminium and Stratasys components did not fail when the maximum load of 294.3N (30kg) was applied. The stiffness of each part was determined by calculating the gradient of each force/deflection graph. For the aluminium and Stratasys parts, the stiffness was calculated from the complete data set. The stiffness of the Markforged component was calculated from the linear portion of the force deflection curve only as indicated by the solid black line. After a deflection of approximately 3.6mm, a large change in stiffness was observed due to carbon fibre reinforcement failure in the material decreasing the part’s stiffness. The results in Figure 1b show that the aluminium had the highest stiffness (439.08N/mm), followed by the Stratasys Nylon12CF (119.41N/mm) and Markforged component

(32.80N/mm). The Markedforged component was determined as not suitable to replace the aluminium part as its strength and stiffness were too low.

The Stratasys Nylon12CF was determined to have the potential to replace the original aluminium part as it had a comparable strength. The stiffness was 3.7 times lower than for the aluminium part and further tests are required to ensure that the higher deformation of the Stratasys part would not impact on the operation of the latch handle. If found to have an impact on the operation, the part would be redesigned with thicker cross-sections to increase the stiffness. Even with increased thickness, the part's mass would still be lower than the aluminium part and costs to manufacture also less.

3.2 Sea Water Inlet Strainer

The 'Sea Water Inlet Strainer' is a component used on a variety of different lifeboat classes to stop debris from entering the engine cooling system. It is currently fabricated from a wrapped stainless-steel sheet and two stainless steel flanges either end. The mass of this component is 1.7kg, its lead time is 3-4 weeks, and its cost is £110. However, due to corrosion issues, the RNLI regularly replaces this part.

As the RNLI want small quantities of this component produced every year, injection moulding was not a viable option. The RNLI engineering team previously considered additive manufacturing as a suitable production method for this component and sent it, in its current form, to 3D printing bureaus for a quote. These quotes came back in excess of £800 per component. This was due to the part not being designed for the AM process. A common misconception of additive manufacturing is that an existing component which has been designed for another method of manufacture can be additively manufactured in its current state. This is of course possible, but by no means gives the best results additive manufacturing has to offer. The original design of the strainer, running it through GrabCAD (Massachusetts, US) slicing software, would require each circular hole to have support material running all the way through. Support material had to run the whole height of the part, and thickness of the overhang to be able to print the top flange. This resulted in a volume of model material of $278x10^{-6}m^3$ and support material of $893x10^{-6}m^3$. The cost of this volume of material in Stratasys ABS-M30 would be £350.

Designing for additive manufacturing is a vital step to achieving the most out of the process. The design changes that were made to this component for additive manufacturing were (Figure 2):

- Increased wall thickness, as the current thickness had been designed for stainless steel so to make sure the ABS part would provide the required impact strength this had to be increased.
- Circular holes were changed to diamond shaped holes. The diamond shape is self-supporting as the next layer never goes over a 45degree overhang to the layer below reducing the requirement for support material.
- The top flange was separated, a lip and groove added to the CAD model, printed separately and then chemically bonded together afterwards.

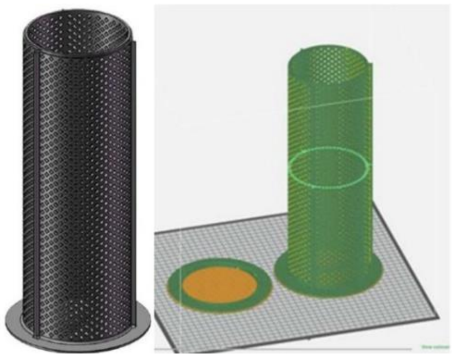


Figure 2. Sea Water Inlet Strainer designed for AM

Using the GrabCAD slicing software on the newly redesigned part, the model material volume increased to $543x10^{-6}m^3$, and the support material volume reduced to $16x10^{-6}m^3$ costing £160 in Acrylonitrile butadiene styrene (ABS). After re-designing this part specifically for additive manufacturing, the new component mass is 0.526kg, new lead time is 3 days, and the new cost is £160. These comparisons show that the AM part in this case is more expensive than the original. However, the AM part will not suffer corrosion problems and will not have to be replaced on a yearly basis, therefore making it more cost effective. To fully validate the AM part, Charpy testing of the impact strength would be required.

4 STUDENT LEARNING

After the research project had provided successful results for using additive manufacturing within the RNLI, the findings were utilised in teaching level 5 (second year) students studying BSc/BA/MDes (Hons) Product Design. To effectively communicate to students the relevant research findings and how they can be utilised within the design and engineering industry, the research results were presented to design and engineering companies and qualitative data was gathered through a questionnaire (Table 2). This data informed what knowledge industry already had regarding designing for additive manufacturing, and highlighted gaps in their knowledge. This guided the dissemination of knowledge to the level 5 programmes, so they were up to date with current industry knowledge and also take new, valuable knowledge into industry with them. The main findings to impart was how additive manufacturing could be used within the design and engineering industry to achieve a streamlined supply chain, offer freedom within design, end use component production, and its impact on lifecycle sustainability, using real-world case studies.

Table 2. Questionnaire results from Industry Dissemination

	Strongly Disagree	Disagree	Neutral / NA	Agree	Strongly Agree
Has your knowledge regarding AM benefits for industrial applications increased from these research findings?	0	0	0	22	12
Has your knowledge regarding designing specifically for the AM manufacturing process increased from these research findings?	0	1	8	17	8
Is your business more likely to investigate the use of AM following these research findings?	0	0	10	15	9

A lecture was delivered to over 80 product design students, to disseminate the research findings and processes. This was an opportunity to give students an insight into both research and enterprise work, and industry practices. Challenges in delivering this research and case studies included how to breakdown over a years' worth of highly detailed research into a one-hour lecture for students who had very little prior experience to industry and research. Denicolo and Becker [9] believe that a good lecture allows students to 'see the results of your research in action', 'be inspired by your enthusiasm', and 'ask you questions'. Therefore, the lecture contained aspects of the research that matched with the unit learning outcomes [10], aspects which were interesting within design for additive manufacturing, so enthusiasm would engage the students, and then also provided a period of time for questions. The lecture centred around the technology used in the research study, as it is technology the students have access to within the university for their upcoming projects, the process of designing for additive manufacturing, and the final outcomes achieved. One of the main purposes of disseminating the research findings to the students was so they could take the knowledge forward and apply it into their upcoming additive manufacturing technology project.

The lecture began with an overview of the clear methodology used throughout the research. This gave the students information from the beginning of the lecture which engaged them and allowed them to understand the process of the research study and not be overwhelmed by the information that would be delivered. The lecture went on to disseminate information regarding the technology investigated in the research, testing and analysis conducted on a variety of case studies, and then final outcomes achieved. To ensure the students would interact with the lecture and take information away from the case studies which they could later apply to their own design for additive manufacturing work, the lecture was interactive and designed to suit a variety of different learning styles. The learning styles included visual, audio and kinaesthetic learners [9], therefore the lecture integrated talking, part demonstrations, images and videos. Videos used in the lecture included showing the process of additively manufacturing parts and then the testing conducted. These videos helped visual learners to further understand the technological processes that were being spoken about during the lecture. Part demonstrations involved taking AM parts from the project into the lecture and allowing the students to pass them around, have hands-on experience, and have discussions about the parts designs and manufacturing techniques, therefore getting the students engaged in the lecture. The mixture of approaches worked well, and received good student feedback, as it constantly kept the students engaged and interested as they had opportunities to talk and discuss the demonstrations amongst themselves then regroup and take in the next lot of information from the lecture. It enabled discussions, questions, and thoughts which otherwise would not have happened. This lecture regarding the research and enterprise work undertaken within the RNLI delivered many positive outcomes, including engaging students, disseminating knowledge and answering questions that students had, this was evident from student participation during the session, the information they carried forward and used in their subsequent additive manufacturing project, and student feedback received.

To follow up and support the dissemination of this research to the product design students, and so they had an opportunity to put their understanding into practice, a subsequent lab session to bring students into the Rapid Prototyping facility at BU was undertaken to physically show them the machines used in the project, show them the processes used to design the parts for additive manufacturing and then a project was set to them to redesign a part for additive manufacturing. This gave them an opportunity to use their skills for designing for additive manufacturing, use the 3D printers, and conduct the post processing that follows so they could have first-hand experience of the whole process. Outputs from this project saw students using topology optimisation to redesign components on a motorbike frame, resulting in lower weight components that could be additively manufactured. This is important as it puts into practice what the students have learnt, offers different learning styles the opportunity to thrive, and gives an opportunity to assess if the learning outcomes of the lecture have been achieved based on what they can do after the learning experience that they could not do before [11].

5 CONCLUSIONS

The findings from this research have been beneficial to both the RNLI, BU staff and the product design students. Knowledge transfer has taken place, benefiting all parties. The benefits that AM could provide the RNLI supply chain and its engineering department have clearly been identified. The students involved have been given real world case studies on how additive manufacturing is being used within the design and engineering industry, enabling them to apply what they have learnt to subsequent assignments.

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