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# "Defining Next-Generation Additive Manufacturing Applications for the Ministry of Defence (MoD)"

Alessandro Busachi[a]*, John Erkoyuncu[a], Paul Colegrove[c], Richard Drake[b], Chris Watts[b], Filomeno Martina[c]

[a]*Cranfield University, Cranfield, United Kingdom*
[b]*Babcock International, Bristol, United Kingdom*
[c]*Welding Engineering and Laser Processing Centre, Cranfield University, Cranfield, United Kingdom*

* Corresponding author. Tel.: +447790779432; *E-mail address:* a.busachi@cranfield.ac.uk

**Abstract**

"Additive Manufacturing" (AM) is an emerging, highly promising and disruptive technology which is catching the attention of the Defence sector due to the versatility it is offering. Through the combination of design freedom, technology compactness and high deposition rates, technology stakeholders can potentially exploit rapid, delocalized and flexible production. Having the capability to produce highly tailored, fully dense, potentially optimized products, on demand and next to the point of use makes this emerging and immature technology a game changer in the "Defence Support Service" (DS2) sector. Furthermore, if the technology is exploited for the Royal Navy, featured with extended and disrupted supply chains, the benefits are very promising. While most of the AM research and efforts are focusing on the manufacturing/process and design opportunities/topology optimization, this paper aims to provide a creative but educated and validated forecast on what AM can do for the Royal Navy in the future. This paper aims to define the most promising next generation Additive Manufacturing applications for the Royal Navy in the 2025 – 2035 decade. A multidisciplinary methodology has been developed to structure this exploratory applied research study. Moreover, different experts of the UK Defence Value Chain have been involved for primary research and for verification/validation purposes. While major concerns have been raised on process/product qualification and current AM capabilities, the results show that there is a strong confidence on the disruptive potential of AM to be applied in front-end of DS2 systems to support "Complex Engineering Systems" in the future. While this paper provides only next-generation AM applications for RN, substantial conceptual development work has to be carried out to define an AM based system which is able to, firstly satisfy the "spares demands" of a platform and secondly is able to perform in critical environments such as at sea.

*Keywords:* Additive Manufactruing, Manufacturing Systems, Defence

## 1. Introduction

This paper represents the results of an exploratory applied research study carried out with Defence Support Services (DS2) providers, Ministry of Defence (MoD), Navy Command Headquarters (NCHQ) and Defence Equipment and Support (DE&S) of the United Kingdom. The aim of the research is to define the most promising next generation "Additive Manufacturing" (AM) applications in the context of the "Royal Navy" (RN) operations and supports. RN platforms are extremely complex entities, featured with a large number of Complex Engineering Systems (CES) and extended or disrupted supply chains. In order to allow the RN's platforms to operate effectively, the DE&S and its industrial partners need to establish "Defence Support Services" systems to provide to the front-end players whatever is required in terms of support. According to [1] AM is an enabler of rapid, delocalised and flexible manufacturing which requires limited space and resources to operate and is able to exploit design

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freedom. Nevertheless, even if AM has a disruptive potential for the RN, current technologies are still not mature enough, are not tailored to the RN applications and requirements and most of all AM technology alone is not the solution to the RN but the core technology of more comprehensive systems. The contribution to knowledge of this paper is given by the definition of future AM applications for the RN, a definition of the problem space faced by the RN, a definition of the opportunities provided by AM to the RN and an exhaustive list of operational aspects of AM. The contribution to methodology is represented by presenting a novel, multidisciplinary and exhaustive approach to technology exploitation and application definition.

## 2. Research Methodology

The novel and multidisciplinary methodology applied is based on Systems Engineering principles developed by [2] [3] [4] and is outlined in Fig. 1.

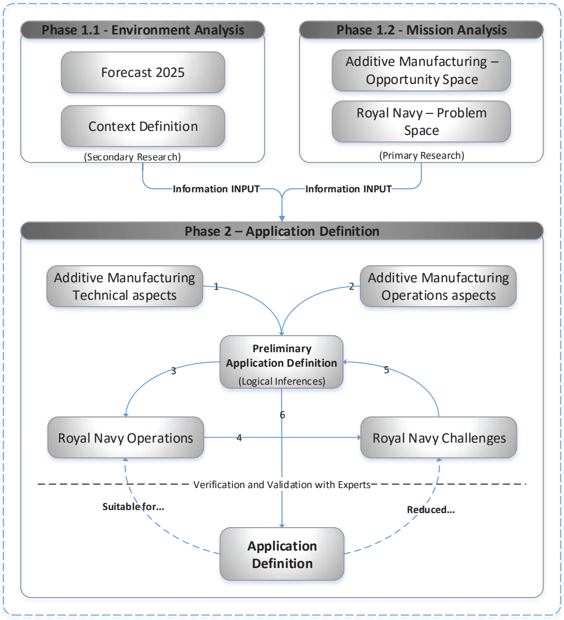

Fig. 1 - Multidisciplinary Methodology

The methodology discerns technical and operations aspects of the technology and combined with macro and micro environment aspects allows to define optimal next-generation applications of Additive Manufacturing.

- *Phase 1.1 "Environment Analysis"* is made of a context definition and outlines a roadmap of how the environment will change in the future. This is mainly carried out with secondary research and sources of information are carefully selected based on reliability.

- *Phase 1.2 "Mission Analysis"* represents a critical activity as this is where the "Context - Problem Space" and "Technological - Opportunity Space" are defined. This is primarily based on primary research and experts were identified from various parts of the whole UK Defence Value Chain. This involved eliciting, capturing, manipulating and validating through expert judgement.

- *Phase 2 "Application Definition"* is a concept development activity based on a conceptual framework which is fed by the results of Phase 1.2" Mission *Analysis"*. This approach allows a systematic AM application definition tailored to RN operations.

In order to feed the "Application Definition" process with reliable information and different perspectives, key experts of the UK Defence Value Chain have been involved. The list of experts is outlined in Table 1:

Table 1 - List of Experts

| Organisation | Position | Experience |
|---|---|---|
| Navy Command Headquarter (NCHQ) | Commander Royal Navy | 30 |
| Support Service provider | Through-Life Support Manager | 30 |
| Support Service provider | Operational Support Manager | 33 |
| Defence Equipment and Support (DE&S) | Technology Maritime Delivery | 30 |
| Defence R&D Firm | Technical Lead | 17 |
| Support Service provider | Technology Acquisition Lead | 10 |
| Defence R&D Firm | Engineering Manager | 10 |
| Research Institute | Researcher | 6 |

The elicitation approach adopted in order to capture the expertise and perform logical inferences to develop conclusions is outlined in Fig. 2.

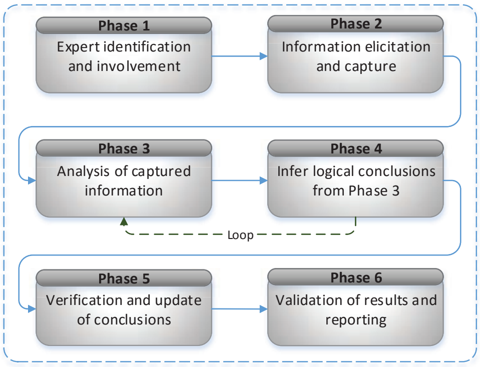

Fig. 2 - Expertise elicitation process

Firstly, organisations of the UK Value Chain have been contacted and requested to nominate an experienced and reliable source of expert. The information elicitation process has been carried out through an induction of the activity aim and through the use of structured charts. Once the information has been captured the results have been analysed. The results have been displayed on an A3 chart with references which allowed the author to have an exhaustive understanding of the overall inputs received. This allowed the author to draw conclusions and report a first draft of the activity. Finally, the draft has been sent to the experts for verification and validation.

## 3. Environment Analysis Results

In 2015, Her Majesty's Government (HM Gov.) has outlined in the National Security Strategy the main objectives of the MoD for the next years of operation. The objectives are summarised in: 1) to protect our people, 2) to project our global influences and 3) to promote our prosperity [5]. In order to do this the HM Gov. allocated a budget of £160 Billion to the MoD for allowing the Armed Forces to achieve the objectives during the period 2015 – 2025 [6]. The budget is allocated mainly for platforms acquisition and support for air, land and sea applications. The entity in charge acquiring and supporting the platforms is the "Defence Equipment and Support" (DE&S) which is part of the MoD. In 2015 the DE&S issued the "Defence Equipment Plan" providing information on how the £160 Billion budget will be spread [6].

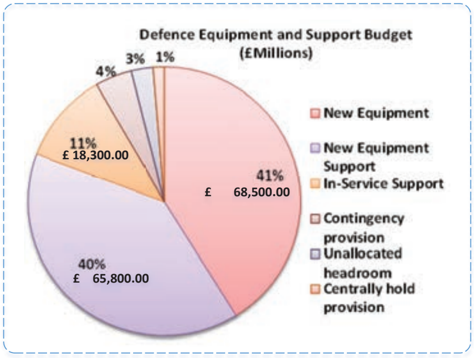

Fig. 3 - Budget Breakdown

As outlined in Fig. 3, £68,500 Million (41%) is allocated to the acquisition of platforms and complex systems and £84,100 Million (51%) to the support activities involved in maintaining the platforms and complex systems [6]. This is an interesting data which shows that the total cost of ownership of defensive platforms is strongly influenced by its cost of operation and support [7].

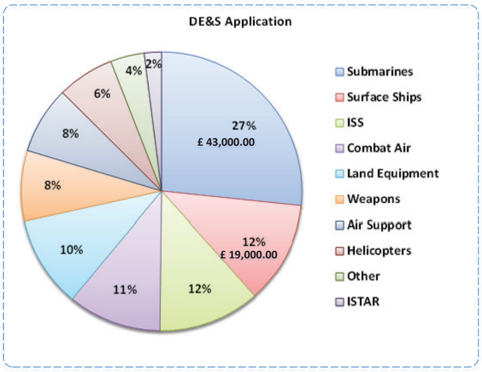

Fig. 4 - Budget for application

Moreover, Fig. 4 reclassifies the budget spending based on application. As outlined in the pie chart, £61 Billion are invested in maritime vessels, both for surface or submerged warfare. Submarines represent the highest investment (£43 Billion) given the critical role they have for national security (HM Command, 2010). The budget of £62 Billion for Royal Navy is employed mainly for design, build, maintenance and acquisition and maintenance of on-board complex systems. According to the MoD (2015), is has been estimated that the defence support activities for the next 10 years will amount to an average of £6.5 Billion per year for maintaining operational Royal Navy, Air Force and Royal Army's in-service platforms [8]. According to the [7] the total cost of ownership of a submarine is broken down as outlined in Fig. 5.

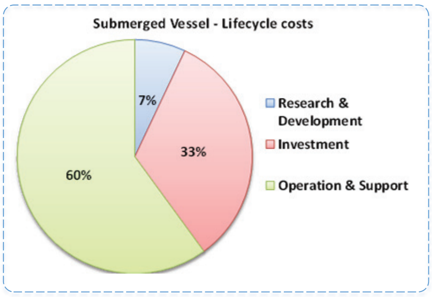

Fig. 5 - Total Cost of Ownership

The "investment" comprises the detailed design, procurement, manufacturing and commissioning of the platform. Operation and support activities amount to 60% of the total cost.

## 4. Mission Analysis Results

DS2 systems are extremely complex realities with high degrees of uncertainties and are triggered by unpredictable or random world events (war, disaster, failures and damages). These systems need to be highly responsive and resilient to cope effectively with the occurrence of these world events. Moreover, DS2 systems play a crucial role in mission effectiveness and accomplishment. Given the large number of CES carried by a defensive platform, the possibility of extended and potentially disrupted supply chains which may cross challenging operating environment, these systems are inefficient by nature and featured by long delay times, starvation, blockage, idle and queues. In order to cope with the inefficient nature of DS2 systems, the DE&S and DS2 providers have put in place all the possible mitigation strategies which allows the RN to operate effectively and deliver its capability around the World. These strategies are to increase the reliability of CES, to hold within the platform critical-to-availability components and consumables, to forecast the "demand" of the platform in different scenarios and to spread spares over the whole DS2 system. Nevertheless, current mitigation strategies are considered extremely challenging and complex and in some cases expensive such as holding large inventories over the whole DS2 system. Moreover, the RN faces also political/military challenges such as being required to be highly responsive to operation tempo, being required to be "multifunctional" and resilient to different mission types and finally the RN is facing strong budget pressure to reduce its costs of support and ownership of the platforms. Furthermore, RN platforms are subject to damages, both, intentionally delivered by hostile entities and unintentional accidents such as fire, floods and collisions. Finally, the RN platforms are expected to operate for long lifetime such as 50 years. Therefore, the platforms may be subject to obsolescence which often has pushed MoD to consider costly lifetime buys which implies also high inventory levels or other inefficient and capital intensive mitigation strategies.

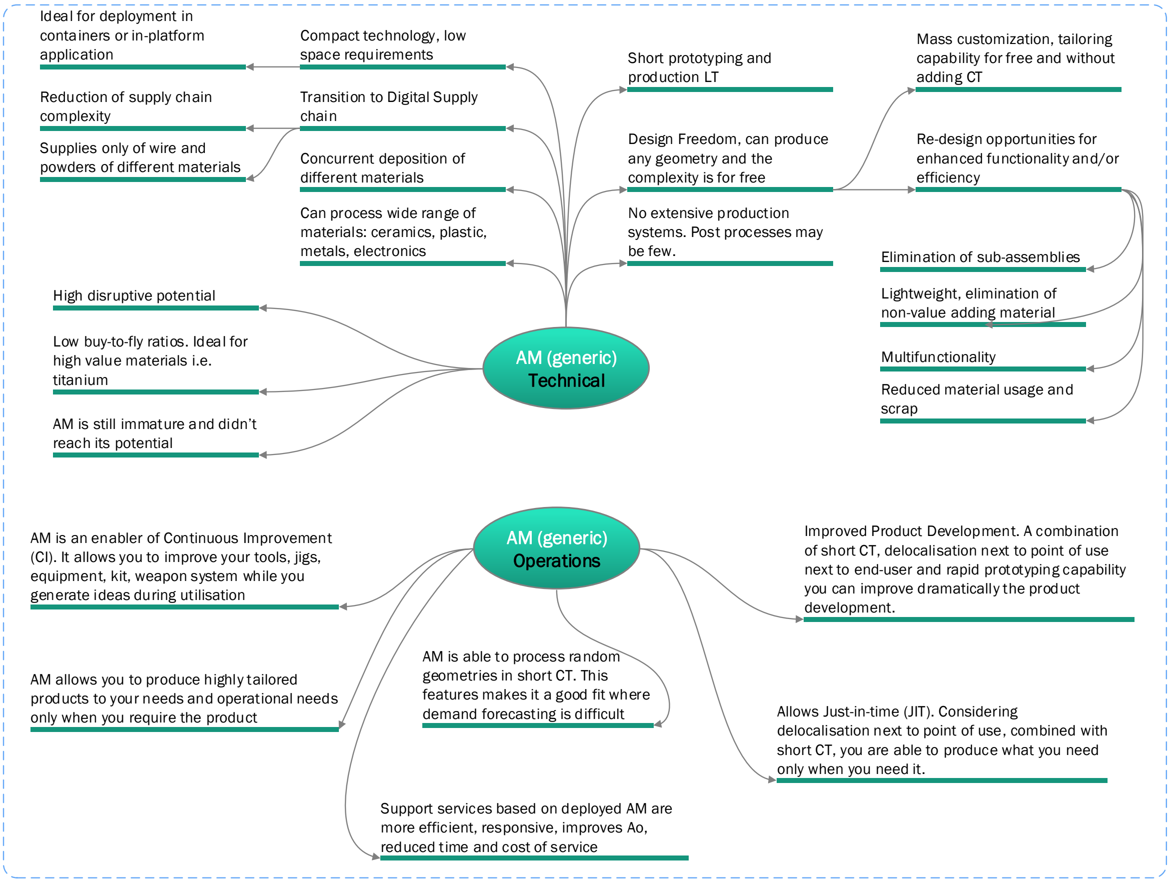

Fig. 6 – Generic AM opportunities

*Opportunity Space:* AM (generic) technical opportunities, which are generally shared (with different levels) among the various AM process methodologies have been outlined and are compactness of the technology, short cycle time for production and prototyping, design freedom, prototyping opportunity to test design in early stage, design for multi-functionality/lightweight/high-efficiency/enhanced functionality, production of fully dense metal/plastic/ceramic parts, concurrent deposition of different materials [9]. AM (generic) operations opportunities have been outlined and are based on "Manufacturing Systems Engineering", "Lean Product and Process Development" and "Lean Manufacturing" principles. These are AM as an enabler of: "Continuous Improvement" (CI) in product development and the workplace, Just-in-Time (JIT) with related reduction of inventory, mass customisation to tailor products to the user needs and features and finally as an enabler of improved efficiency of the DS2 system through delocalisation.

The most important opportunity provided by AM, is design freedom. If compared with traditional manufacturing, where material is removed, AM allows designers to access freeform design and achieve new geometries which wouldn't be feasible with conventional manufacturing systems. [10] outlines that, if AM is associated with appropriate design methodologies, topology optimization software and structure analysis tools, the technology can provide improved components in terms of functionality and efficiency. This combination of technology, tools and methodology allows to shift the design paradigm from "feature based design" to "function based design". This opportunity provided by AM is particularly appealing for high performance industries such as Aerospace and Motorsport, where "stiffness-to-weight" ratios are a critical aspect of components. Moreover, [11] outlines the notable impact of design freedom provided by AM in the heat management sector. Internal freeform geometries allow designers to create complex internal features to increase the efficiency of heat exchangers and improve performance with the same volume of components. Furthermore, [12] explains that design freedom can be exploited to reduce or eliminate sub-assemblies and achieve part consolidation. If coupled with a part consolidation method, designers can focus on function integration and achieve performance improvement. This is supported by [10] which outlines a case in the Motorsport sector where traditionally glue is utilised to stick together sub-assemblies.

The captured inputs have been reorganised and outlined in Fig. 6 differentiating between technical and operations opportunities provided by AM.

## 5. Conceptual Framework

In order to define systematically next-generation AM applications in the context of RN, a conceptual framework has been developed and is outlined in Fig. **7**. This is based on the inputs received, manipulated and reported in Phase 1.2 “Mission Analysis Results”. The conceptual framework is made of four distinct but interconnected areas, “Technology – Technical”, “Technology – Operations”, “Platforms Operations” and “Environment Challenges” which lie inside the “Environment Definition”. This approach, allows to define systematically promising AM applications for the RN context taking into account operational and technology aspects. The conceptual framework is represented as a Venn diagram which by nature does not provide information on sequences but outlines all possible logical relations between different sets and their intersection.

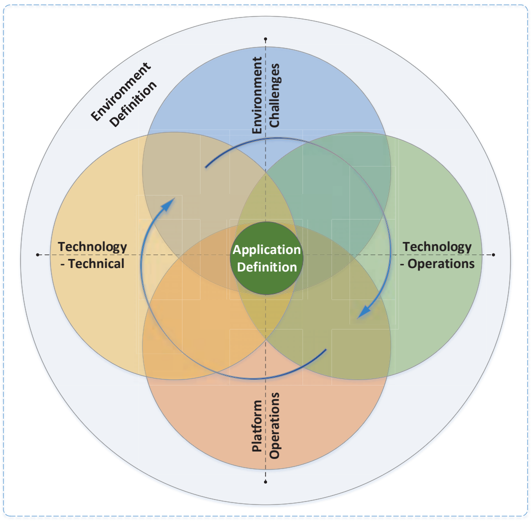

Fig. 7 - Conceptual Framework

While in Fig. 7 a sequence of the logical inference for application has been developed, in Fig. 7 this has been omitted as one might argue that different sequences may be adopted and are equally viable. Nevertheless, the author has followed the following rationale: *“Given these set of technical and operational aspects, which are beneficial in these types of RN operations, the technology may be exploited to solve these types of environmental challenges and provide the potential advantages”*. In order to eliminate the development of paradoxical definition of applications, the results have been sent to experts for verification, validation and limits definition.

## 6. Application definition results

This section outlines the most promising next generation applications of AM for the RN and has been ranked based on financial, operational and military impact. The result is:

*“to exploit AM opportunities to delocalise manufacturing to the front-end of a DS2 system and within the platforms to support CES or recover capability after being subject to accidents or battle damages (print or repair components)”*.

The result is given by a combination of technical aspects such as compactness of technology, fully dense metal production, design freedom, rapid production and operations aspects such as enabler of JIT, ability to process random geometries and ability to delocalise manufacturing to different stages of the DS2 system. Other promising next generation AM applications are as follows:

- Develop deployable AM units to support disaster relief missions with the ability to print simple plastic medical components (valves, pipes, fittings) and more sophisticated AM units to print temporary or permanent tailor made prosthetics.

- Delocalise manufacturing within the platforms or develop deployable AM units for forward bases to support specific soldier’s needs and tailor body armours, kit, special tools or small arms to the unique operators features and mission requirements.

- Delocalise manufacturing within the platforms or develop deployable AM units for forward bases to print or repair “Unmanned Ground/Sea/Air Vehicles” (UV).

## 7. Discussion

Providing AM capability to different locations of a DS2 system such as a forward base, support vessel or defence platform to print or repair critical-to-availability components and print new components or structures to recover capability after being subject to battle damages or accident provides the following benefits:

- Dramatic reduction of the “Logistic Delay Time” (LDT) which reduces firstly the cost to deliver the support service and secondly improves the Operational Availability of CES.

- The inventory level drops given the use of AM only when a component is required. This aspect has both financial advantage and also provides more free space to the platform.

- Responsiveness to operations tempo, efficiency and resilience of both the DS2 system and platform improves dramatically providing strategic advantages.

- Platform’s autonomy, lethality, survivability, vulnerability improves allowing the platforms also to perform better in unestablished or disrupted supply chains.

Nevertheless, AM technology alone is not able to cope with the challenging requirement of the previously outlined “promising application”. A Hybrid AM system needs to be developed and tailored to the application aim which is to print new components and repair broken ones in a challenging environment. Moreover, current AM technologies such as “Selective Laser Melting” (SLM), “Electron Beam Melting” (EBM), “Laser Cladding” (LC) and “Wire + Arc Additive Manufacturing” (WAAM) need to be reviewed technically and a selection of which AM technology is most suitable to the RN has to be carried out.

Table 2 - Operating Environment requirements

| Needs | Description |
|---|---|
| Vibration (Input) | The Platform may be subject to strong vibrations |
| Vibration and Noise (Output) | The installed equipment may deliver vibrations or noise which can increase the likelihood of detection of the platform |
| Shock | The Platform might be subject to explosive-based shock events |
| Controlled Atmosphere | In some Platforms atmosphere is controlled therefore aspects such as oxygen consumption, heat, humidity, exhaust gas outputs needs to be controlled |
| Oscillations | Some Platforms may be subject to oscillations and unstable situations |
| Autonomy | Some Platforms can require operation for up to 3 months without external replenishment of consumables |
| Utilities | Utilities in Platforms are limited |
| Volume and Weight | Platforms have limited tolerance for any additional changes in volume and weight from the design baseline |
| Corrosion | Equipment might be subject to corrosive agents such as water and salt |
| Safety | Equipment's materials need to satisfy the regulations |
| Mission Critical Environment | Equipment needs to be highly reliable and robust in order to perform when required to do so |
| Waste Management | Waste has to be minimized and recycling aspects need to be investigated |

Moreover the Hybrid AM system has to be assessed quantitatively against the RN operating environment requirements outlined in Table 2 by [1].

## 8. Conclusion and future work

This paper summarizes the results of an exploratory applied research study carried out with representatives of the UK Defence Value Chain. The aim of the study is to investigate, with a Systems Engineering approach, promising next-generation applications of Additive Manufacturing for the UK MoD, more specifically for the Royal Navy platforms. The authors have spent effort in focusing on the most promising future applications of AM (2025 – 2035 decade), therefore the experts involved have been encouraged to adopt an elastic, creative approach and abandon constraints given by current limitations and AM maturity. In order to avoid paradoxical results, a solid and novel methodology has been developed and adopted to carry out systematically the exploratory study. Moreover, experts with different perspectives have been involved to provide primary information and also for verification and validation at different stages on the study. The study started by defining the high level environment in which MoD operates and the forecast of how the environment will change in the future. The challenges faced by MoD have been outlined and AM technological opportunities have been defined. These results have been manipulated and reorganized and a conceptual framework has been developed in order to define the most promising next-generation AM applications for the Royal Navy. The results show that AM is an enabler of JIT and delocalized manufacturing which combined with design freedom and fully dense metal production can have major impact on the support service sector.

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# Defining next-generation additive manufacturing applications for the Ministry of Defence (MoD)

Busachi, Alessandro

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