Modelling Applications of Additive Manufacturing in Defence Support Services: Introducing the AM - Decision Support System

Alessandro Busachi CEng, Dr. Daniel Kuepper, Dr. Jacopo Brunelli, Dr. Wilderich Heising Dr. Clemens Moeller, Dr. Drosten Fisher, Dr. Chris Watts, Dr. Richard Drake

The Boston Consulting Group (BCG)
Via Ugo Foscolo, 1, 20121, Milano

Babcock International
Ashton House, 1, BS32HQ, Bristol

Busachi.Alessandro@BCG.com

ABSTRACT

Additive Manufacturing (AM) is increasingly gaining the attention of Defence Support Service (DS2) providers and NATO's Ministry of Defences (MoD) due to its capability of rapid, delocalised and flexible manufacturing. Deploying AM systems in the front – end of a military logistic can provide major advantages to both the MoD and the DS2 provider. Printing required components next to the point of use can lower the time and cost of delivering support services. Consequently, the Availability of Complex Engineering Systems (CES) increases, allowing the Platforms to be more responsive to operation tempo. This paper aims at presenting to the NATO alliance the "Additive Manufacturing – Decision Support System" (AM-DSS) a cloud based software platform, which can perform simulations of AM deployments in military logistics and provides the user with accurate cost and benefit analysis results. The software allows the users to compare a traditional military logistic where stocks are held in various stages (manufacturing occurs at the supplier's facility) with AM military logistic, where manufacturing can occur at a port, a support vessel, a forward base or the defence platform through deployable AM Systems. The software tool is developed for key decision makers of the NATO's MoDs to adopt a data driven approach for AM technology acquisition programs.

1.0 INTRODUCTION

This paper aims at presenting to the NATO alliance an applied research program titled "Additive Manufacturing – Decision Support System" (AM - DSS). The AM - DSS is a cloud based, software platform, which allows users to perform simulations and cost benefit analysis of the deployment of different AM technologies in various stages of a military logistic. The software allows the users to compare a traditional military logistic where stocks are held in various stages (manufacturing occurs at the supplier's facility) with AM military logistic, where rapid manufacturing can occur at a port, a support vessel, a forward base or the defence platform through deployable AM Systems. The AM – DSS is developed for key decision makers of the NATO's MoDs involved in Additive Manufacturing technology acquisition programs. The AM – DSS presented in this paper has been further developed based on the results of the PhD tilted "Modelling Applications of Additive Manufacturing in Defence Support Services". The PhD sponsored by Babcock International and awarded the NATO – Defence Innovation Challenge in 2017, the Swiss INCOSE Prize in 2017 and Commended for Excellence by the UK MoD in 2016.

This publication includes work, research and results from the PhD Thesis Modelling Applications of AM in DS2, sponsored by Babcock Integrated Technology Limited in which Babcock Integrated Technology Limited retains the IP rights, and research developed after the PhD Thesis

2.0 LITERATURE REVIEW

This section focuses on presenting a brief literature review on AM in Defence, Wire + Arc Additive Manufacturing and Cost Modelling techniques to model the product cost and lead time of AM.

2.1 AM in Defence

Ivanova, Williams, & Campbell, (2013) defines "Additive Manufacturing" (AM) as a group of emerging and promising technologies that create an object by adding material bottom-up. AM enables rapid conversion of CAD files into physical products by merging layer upon layer of heated material RAND (2013). It is defined as the "process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methodology"(ASTM, 2013). Exploiting "Additive Manufacturing" (AM) opportunities for "Defence Support Services" (DS2) is a fairly new concept. Pérès & Noyes (2006) introduced the concept of spare parts production with AM, on request and in short time for isolated platforms in which space is a constraint such as orbital stations and generic military equipment. The conclusions of their study were the demonstration of the feasibility of the concept. The main limitations outlined were the immaturity of AM technology. Iwata & Mavris (2013) developed a dynamic model to simulate DS2 for aerospace vehicles. With this research, the importance of dynamic simulation for DS2 was outlined. Moreover, they outlined that 60% to 70% of total cost of ownership of a defence platform relies on support services and maintenance.

Khajavi, Partanen, & Holmström (2014) combined DS2 with AM and dynamic simulation and evaluated the impact of AM implementation of support services for F-18 Super Hornet Fighter jet. The research investigated a set of possible supply chain configurations with delocalised manufacturing. Major barriers outlined were the AM equipment cost and personnel intensiveness. Busachi et al. (2015) investigated wire based AM technology for support availability of system on defensive platforms. In the same year Busachi et al. (2017) investigated the available AM technologies and related approaches to measure the product cost. Apte & Rendon (2009) carried out a research on the optimisation of availability of systems on Navy platforms. According to their conclusions in order to improve the availability of a complex weapon system, it is crucial to ensure: 1) quality of spares which implies higher reliability and longer life of the component, 2) availability of spares on board in order to reduce delay times and 3) establish a well-structured preventive maintenance cycle to reduce failure rates of the system, 4) perform "5 Whys" or "Root Cause" Analysis on components that fail and assess criticality of failure with respect to mission success and finally 6) establish performance based contracts with external contractors to improve cost-reduction activities.

The current industrial applications of AM within the defence sector have been reviewed. MBDA is a leading European consortium in the missile industry. The consortium has introduced AM in its business since 1988. Initial application of AM was Rapid Prototyping to support the product development phase and reduce the time-to-market of new designs. In a second phase AM has been used to produce complex tooling solutions. In recent years, MBDA decided to exploit the potential opportunities arising from AM and expanded its Research and Development activities. In 2011, they established a collaboration with Cranfield University's Laser Processing and Welding Engineering Centre. The focus of the collaboration was "Wire + Arc Additive Manufacturing" (WAAM) process methodology to print Missile structures made of Titanium (Ti6Al4V) MBDA (2015). Another important player in the application of AM in Missile sector is the "Aviation and Missile Research Development and Engineering Centre" (AMRDEC) of the US Army (US Army, 2015). The centre has a collaboration with NASA and the University of Alabama. In May 2014, the Centre, established a Research and Development team called Integrated Product Team (IPT) that works on the application of AM for the manufacturing of missiles. The main research aim is to develop a stronger and lighter structure, which can manage the strong vibrations that occur during flight. In 2010 the US Army established the "Rapid Equipping Force" (REF) to support the Army in Afghanistan (REF, 2015). The Mission of the REF is to provide immediate solutions to the urgent challenges faced by soldiers. This has been possible through the deployment of mobile laboratories called “Expeditionary Labs”. These labs are based on an AM system and a CNC machine and a multidisciplinary team made of scientists and engineers. Each lab has a cost of around $2.8 million. REF has been considered a successful solution for the development of non-standard quick reaction equipping of US soldiers. This is due to its ability to provide the Army with customised solutions to changing missions and environment. The labs aim to produce low volume quantities, more specifically “limited quantities of specialised capabilities”.

2.2 Wire + Arc Additive Manufacturing

According to Ding et al. (2011) “Wire and Arc Additive Manufacturing” (WAAM) is gaining industry attractiveness for the production of large, custom made, near-net-shape metal components due to its versatility and high deposition rates.

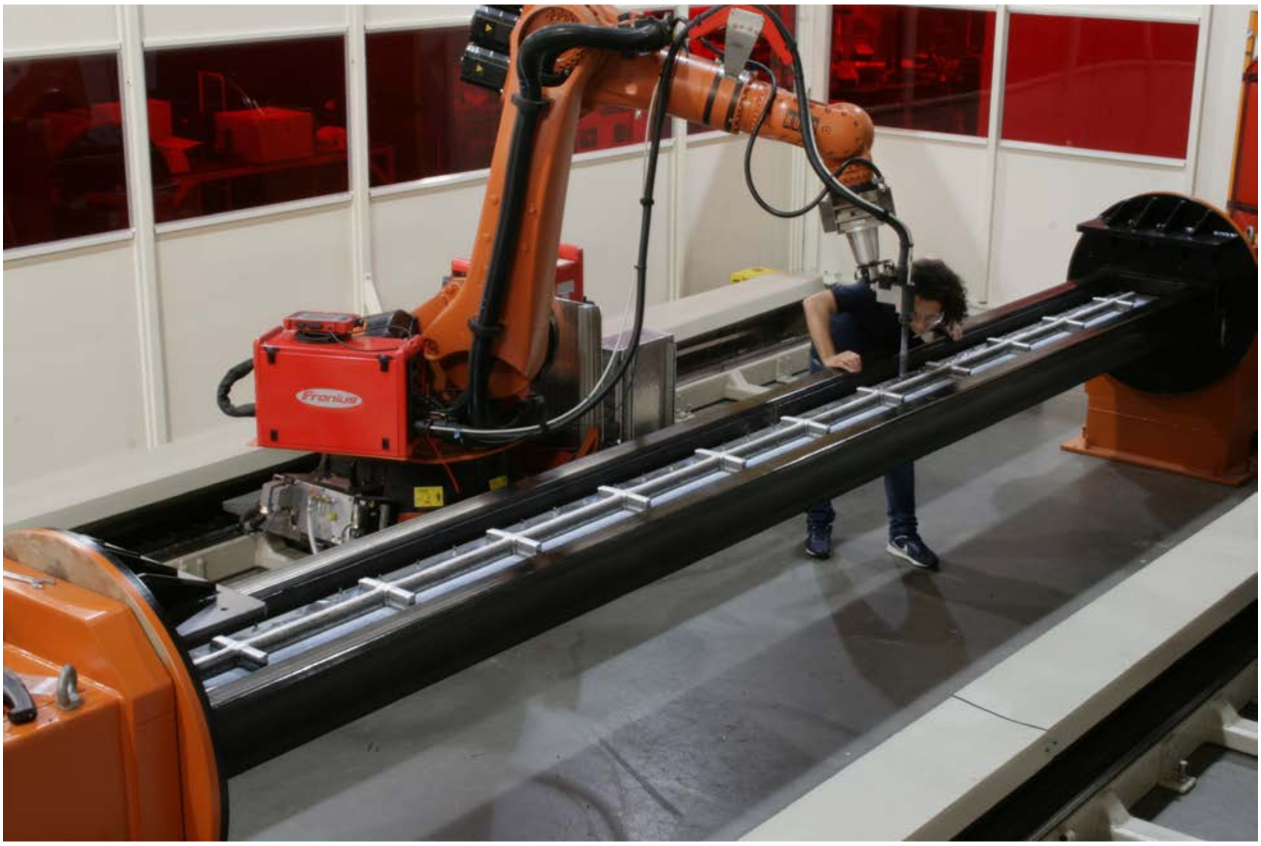


Figure 1 - WAAM System in Cranfield University

As defined by Wang, Williams, & Rush (2011) WAAM is an additive manufacturing process which uses TIG, MIG or Plasma torches to manufacture components by adding sequential layers of material from a wire feedstock without the need of tooling. The system is made of a power source, which is the welding machine, a motion control system that is the robot, the torch for controlling the arc, a wire feeder and a chamber. QIU (2014)) outlined several advantages of WAAM process such as the possibility to process super alloys, creation of large parts, high deposition rates, reduction of residual stress due to on-line rolling process. Chen (2012) stated that this technology could reduce BTF ratio by 30%-40%. The results were impressive as the implementation of WAAM process could save around 3,000 tons of material. Ding et al. (2011) carried out a thermo-mechanical analysis of large scale components produced with WAAM process. They concluded that the stress across the deposition area is uniform while the part is clamped. Furthermore they outlined that after unclamping of the work, the stress is redistributed Ding et al. (2011). Martina et al. (2012) carried out an investigation of the benefits of WAAM process based on plasma deposition for the manufacturing of Ti6Al4V components for aerospace industry. They demonstrated the feasibility of the process for large aerospace structural components, defined a process envelop outlining the correct combination of process parameters. Nevertheless Martina et al. (2012) outlined that oxidation and distortion could become an issue.

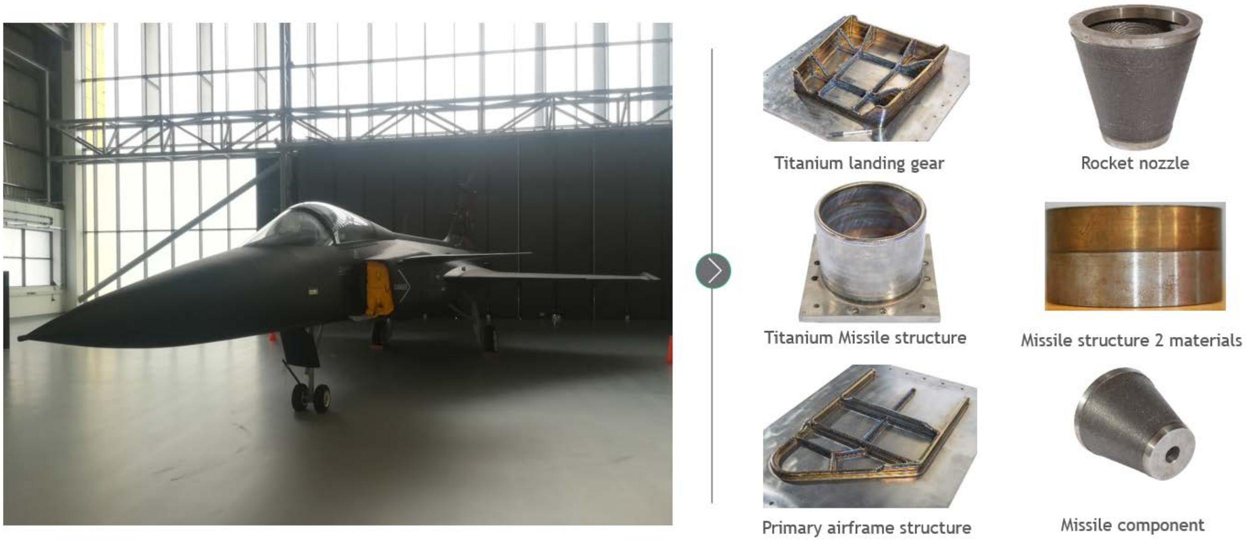


Figure 2 - WAAM Applications in Aerospace

Currently, Cranfield's Welding Engineering and Laser Processing Centre developed a new process called Rolled WAAM, which shares the same principle of WAAM process with the extension of a roller tool, which performs on-line deformation to decrease the residual stress of the component. Colegrove et al. (2013) outlined that components processed with WAAM have strong distortion, residual stress and large grain size. This is mainly due to the high heat input of the arc. There is a need to develop mitigation methods to increase the quality of the components. After performing experimentations Colegrove et al. (2013) concluded that the rolling process can significantly reduce the peak of residual stress and distortion of the material. Moreover, "slotted" rollers limit the lateral deformation of the sample with a better reduction in residual stress and distortion compared to the "profiled" roller. Another important conclusion which has a significant impact in terms of lead-time is that if, the rolling activity is performed every four layers, it has a similar result compared to rolling every layer. Rolling has a significant impact on the microstructure of the samples. Colegrove et al. (2013) states that rolling enhances the grain refinement. Adebayo (2014) has studied the implication of solid lubricant application during the process. They concluded that also after cleaning the surface with Acetone, the traces of lubricant are still present and they affect the microstructure and hardness of the deposited material. More precisely the presence of lubricant increases the grain size and consequently reduces the hardness of the material. There is a need to identify the correct procedure and lubricant for applications such as rolling and machining of WAAM deposited material. The technology is matured till TRL-8, it is employed for large medium complexity components and can print Aluminium, Titanium and SS. The main quality issues and challenges are related with lack of fusion and porosity. The technology is not industrialised but the feasibility is demonstrated for printing large customised metal components up to 6 mt in length moreover in recent years Cranfield was able to deliver also complex features such as enclosed structures, crossing structures and balanced building structures. The main challenges are related with the software side. The re-design for WAAM and the development for the deposition strategy and deposition path is not automatic and requires highly skilled human effort. Also defining the process parameters is a challenge. Currently Cranfield is focusing on tackling these challenges coupled with the development of online monitoring system to control the geometry deposition.

2.3 Cost Modelling for Additive Manufacturing

Hopkinson & Dicknes, (2003) developed a cost model to provide direct comparison between “Additive Manufacturing” (AM) and injection moulding. The AM process has been broken down into machine cost, labour cost and material cost. The cost model developed is based on expert judgement, extended and educated assumption and fed by a wide range of data. Ruffo, Tuck, & Hague (2006) advances the cost modelling on AM with the development of a cost model which considers the high impact of investment and overheads of modern manufacturing processes. The cost model considers activities associated with AM and divides them into direct and indirect costs. These activities have been translated into hourly rates (£/hour) providing evidence of the application of “Activity Based Costing” (ABC) technique. The developed “Cost Breakdown Structure” (CBS) included labour, material, machine absorption and production/administrative overheads. Moreover, the authors were able to model the costs associated with the alteration of the orientation of the part within the build chamber. (Lindemann, Jahnke, Moi, & Koch, 2012) Provided a further development into cost modelling for AM introducing a more consistent way of applying “Activity Based Costing” (ABC) and “Event Driven Process Chains” (EDPC) for costing AM. The cost model has been developed to estimate the life-cycle costs of AM including the costs occurring from the conceptualisation of the design until the disposal of the product. Lindemann’s approach is based on process analysis, cost drivers analysis and product life-cycle analysis. The cost model implements “Time Driven Activity Based Costing” (TDABC) as a computation technique. According to (Lindemann et al., 2012) geometrical complexity is a strong influencing factors on the product cost estimate as this has an impact on the cycle time of the machine. Moreover, the need for more accurate deposition time estimation is required. (Zhai & Lockett, 2012) developed an early stage cost model to compare the costs of “Wire + Arc Additive Manufacturing” (WAAM) technology and CNC. As WAAM technology is featured with high deposition rates, medium design freedom, it is applied to large aerospace structural components and the focus of their cost model is to provide an accurate product cost estimation but mostly outline a comparison with CNC.

3.0 METHODOLOGY

As follow, a description of the phases of the methodology adopted to develop the Additive Manufacturing – Decision Support System (AM-DSS):

- Phase – 1 “System of Interest” (SoI): this represents a conceptual modelling activity which seeks to define the boundaries of the investigated system (DS2 and AM), its elements, sequences, links, triggering events and dynamics.

- Phase – 2 “Business Process Mapping” (BPM): this is the sequential conceptual modelling activity which provides a further level of information on the DS2 and how it delivers value through its processes.

- Phase – 3 “Cost Breakdown Structure” (CBS): fed by the SoI and BPM, this phase looks at defining at a conceptual level the CBS. The CBS represents also the desired Model output

- Phase – 4 “Mathematical Model”: fed by the SoI, BPM and CBS, this phase aims at developing the equations which represents the occurrence of costs during the process of delivering value. This phase is based on the work of (Zhai & Lockett, 2012).

- Phase – 5 “Model Architecture”: this phase aims at studying and defining the logic of the AM-DSS, how the code should be written, what are the inputs/outputs, how to display them to make them significant and how to keep the model flexible in order to make it functional.

4.0 CONCEPTUAL MODEL OF A DS2 SYSTEM

As outlined by Busachi et al. (2017) and Sabaei et al. (2017) a Defence Support Service (DS2) system is made of various organisations which interact together to keep a defence platform "operational" and able to deliver its capability through its Complex Engineering Systems (CES). The organisations are The Royal Navy which operates the defensive platform, Ministry of Defence (MoD) which manages its contractual support, the DS2 provider which is in charge to deliver support to ensure availability of CES and the suppliers which retain the Intellectual Property of the CES and the components.

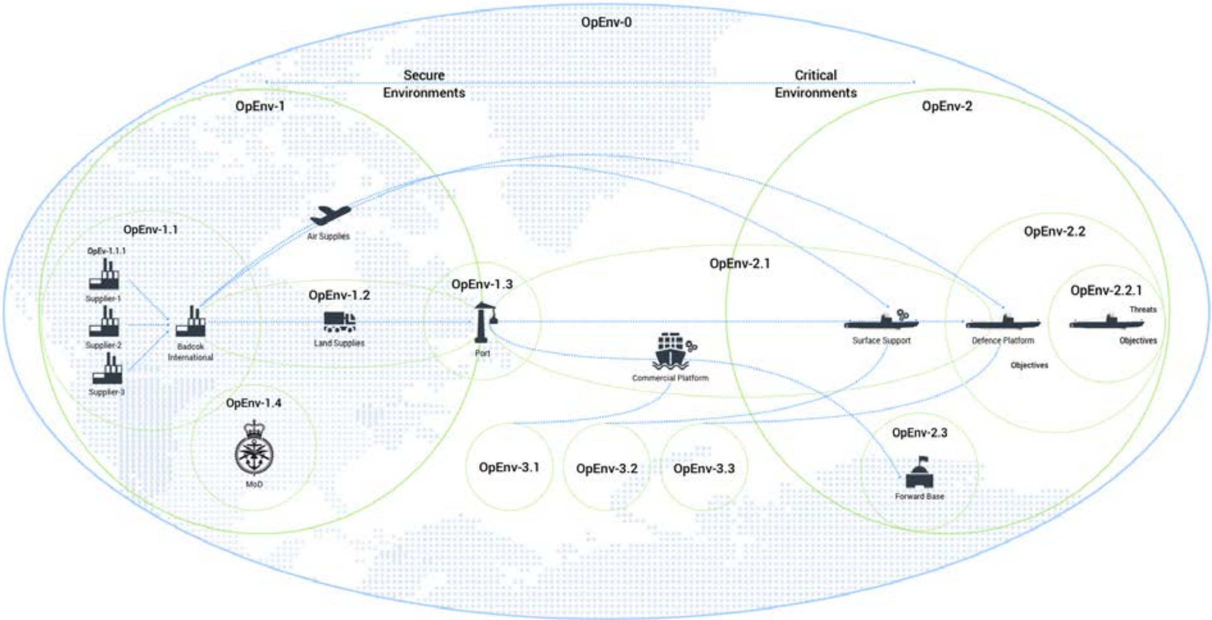


Figure 3 - Conceptual Model of a DS2 (see Appendix – 1)

The Royal Navy's platforms are aircraft carriers, destroyers, frigates and submarines which are featured with the ability to operate everywhere in the world in complex and critical environments. This implies that a Royal Navy's DS2 provider must cope with extended supply chains. In some cases, these supply chains may be disrupted such as situation of battle theatre where the presence of threats may limit operations. The Royal Navy is involved partially with the DS2's operations and perceives value through a "Key Performance Indicator" (KPI) of the complex systems to be supported, which is availability. Availability is a measure of uptime over total-time (uptime and downtime) and measures the predicted ability of a CES to achieve its purpose when required to do so.

The MoD outsources to the DS2 provider the support to the availability of CES through "Contracting for Availability" (CfA) or "Spare parts contracts". CfA contracts imply that the parties agree to maintain a certain level of availability over a period (i.e. 10 years). Spare parts contracts are simple delivery of components when they fail. When the MoD triggers the DS2 provider to restore the availability of a system, the DS2 provider oversees: 1) quoting the component cost, service cost and time of service, 2) if successful, purchasing the component, 3) delivering the component to the platform and finally 4) disassembling the system, installing the component, assembling the system and commissioning the system.

If a DS2 is represented as a system, it is made of N°8 "System Elements" (SE) which are: 1) Supplier facility, 2) DS2 provider facility, 3) MoD facility, 4) Port facility, 5) Surface support vessel, 6) commercial vessel, 7) defence platform and 8) forward base. These SE are connected through links, which define the way a DS2 can deliver value to the Royal Navy. The links are 1) logistics, 2) administration and

3) procurement. As outlined, a DS2's SE are strictly linked together and through the interaction between the SE the DS2 is able to support the availability of CES on platforms. As can be deduced, a DS2 is triggered by the change of state of the CES. A CES has three states: 1) Operating, 2) Standby and 3) Down.

A CES's state is triggered by the occurrence of events. These events are threats, targets and random failures. When a threat occurs, a CES operates to eliminate that threat. When a target is clear, a CES operates to hit it. When a system is "Operating" or in "Standby", the system is available and consequently the DS2 system is in pause.

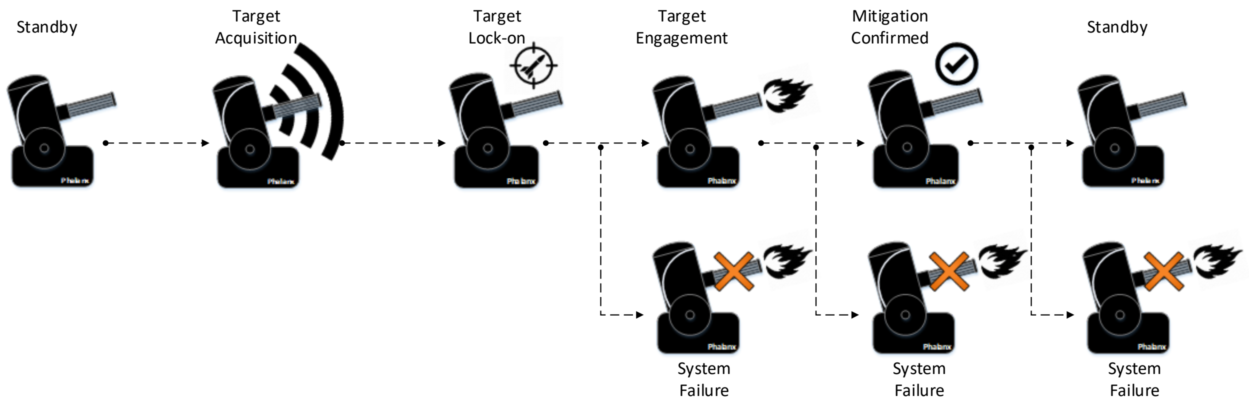


Figure 4 - CES System Dynamics

The CES has a sequential behaviour, which is featured with randomness (i.e. Cycle Times may vary). The behaviour is a process that follows a Boolean logic (true, false) at each stage. The system may be subject to wear or random failures before, during and after the engagement phase. The CES is a passive system, which works through the interaction of components that are critical-to-availability.

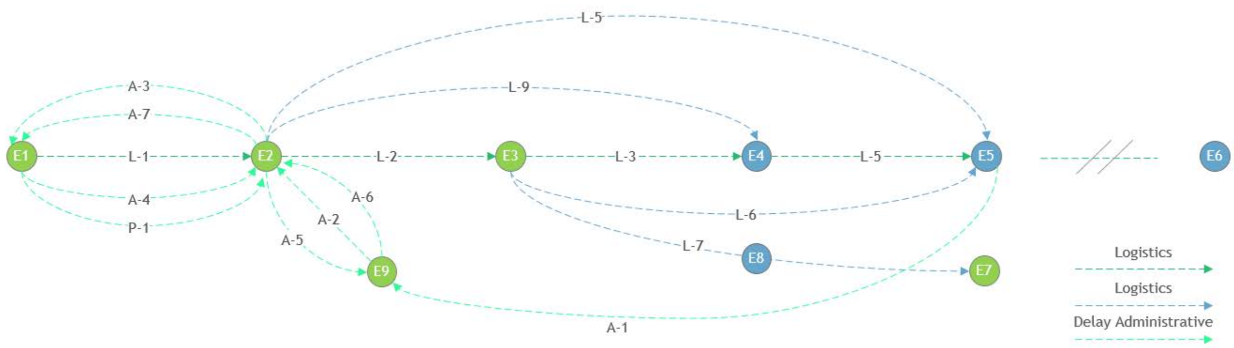


Figure 5 - DS2 Procurement and Delivery (see Appendix – 1)

When the CES is "Down" the DS2 system is triggered and required to operate to do whatever to restore the availability of the CES. The "Down" state of the system starts when a failure or damage (events) occurs. The "Down" state is measured in terms of time (i.e. hrs) and equals the amount of time required to replace the failed component with a new one. This is given by the "Administrative Delay time" (ADT), "Procurement Delay Time" (PDT), "Logistic Delay Time" (LDT) and "Corrective maintenance" (CM). When a platform is deployed remotely, the most influential factor on Availability is given by the LDT. Moreover, platforms are featured with space scarcity, which limits the number of spares they can carry. Furthermore, when platforms are deployed in Area of Operation where combat situation occurs, the supply chain may be disrupted and support vessels such as The Royal Auxiliary Fleet may have limited freedom in operations failing in delivering support to the platform.

4.1 System Configurations (SysCos)

A defence platform is an active and deployable SE, and is engineered to operate everywhere in the world. This may result in extended supply chains. If a required spare part is not available on board, it must be shipped from where the spare part is located (i.e. support vessel, port, DS2 facility or supplier facility).

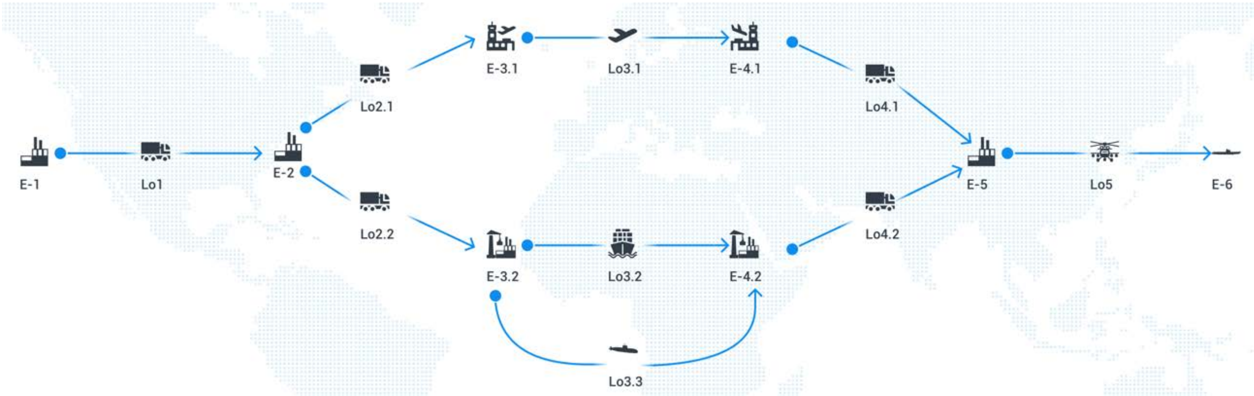


Figure 6 - System Configurations (see Appendix – 1)

Distance and speed of delivery of component and competences are critical factors to availability. “System Configurations” (SysCo) refers to all the possible options a DS2 provider has, to deliver spare parts to Royal Navy’s platforms. SysCos have been sequenced from fastest to slowest, it is assumed as a rule that the spare part holder or manufacturer is E1 and there are no available spares held in the supply chain.

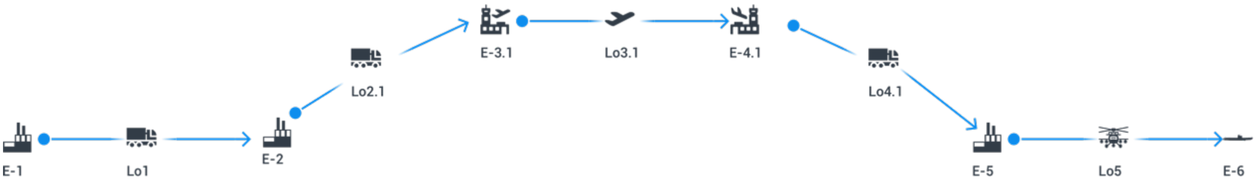


Figure 7 - SysCo3

- *SysCo1* outlines a scenario where a defence platform is not deployed and located at the port. SysCo1 is therefore made of L1, L2, L6 (land, land, port) which are fixed and known distances between elements located in safe environments.

- *SysCo2* outlines a scenario where the defence platform is deployed in an operational theatre; therefore it is serviced by a supply chain. SysCo2 is made of L1, L5 (land, air), L1 distance is known while L2 distance is highly variable and scenarios must be outlined.

- *SysCo3* outlines a secondary air supply scenario where the spare part is delivered through air to a surface support vessel which will approach the defence platform in a secondary phase. SysCo3 is made of L1, L9, and L4 (land, air, sea). L9 and L4 distances are highly variable.

- *SysCo4* outlines a scenario where a surface support vessel is located at the port and will approach the defence platform in a second phase. SysCo4 is made of L1, L2, L3 and L4 (land, land, sea, sea). L1, L2 and L3 distances are known while L4 is again highly variable depending on the location of the platform

- *SysCo5* outlines a scenario where a commercial vessel is located at the port and will approach a forward base in a second phase. SysCo4 is made of L1, L2 and L7 (land, land, sea). L1 and L2 distances are known while L7 varies based on the location of the forward base.

5.0 CONCEPTUAL MODEL OF A HYBRID AM SYSTEM

According to Busachi et al. (2015) fully integrated Hybrid AM systems are highly promising for the defence and military sector given their deployability In-Theatre. Through the delocalisation to the front-end of a support service both, the MoD and the DS2 provider may have strong benefits. The MoD may benefit from increased availability of CES and increased responsiveness to operation tempo, while the DS2 provider may have lower cost of services and consequently become more profitable.

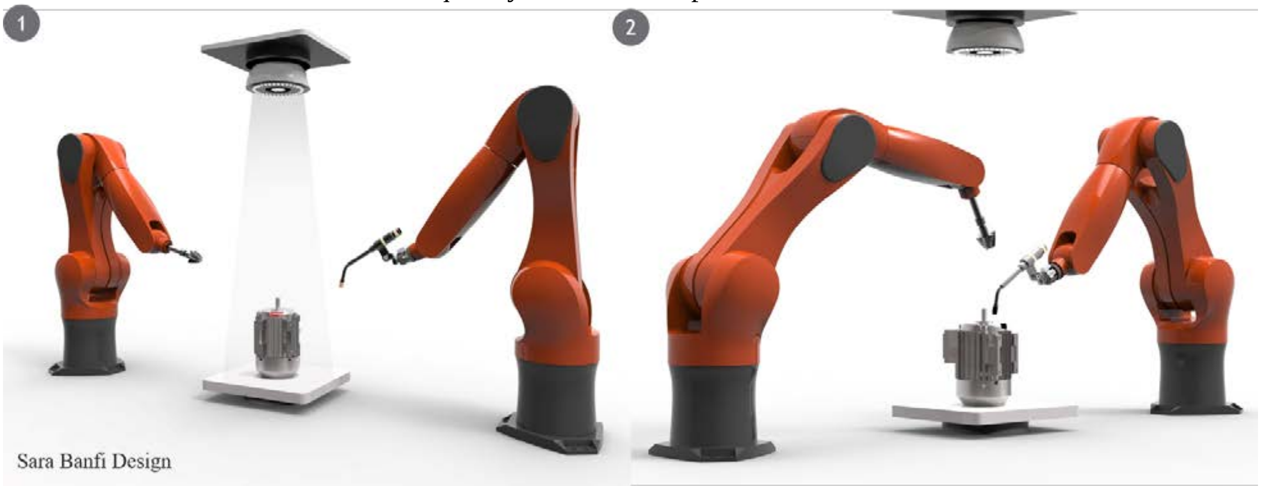


Figure 8 - Hybrid AM System

This section investigates a Hybrid AM system outlined in Figure 8 based on WAAM technology, 3D Scanning, Milling and damage analysis software tool and is intended for both, printing new components and repairing broken ones. The IDEF0 in Figure 9 outlines an "Integration Definition of Function Modelling" (IDEF0) of a Hybrid AM system, which has been developed to gather a deeper understanding on what are the operations, inputs, outputs, controls and mechanism of the system. The aim of the IDEF0 is firstly to provide a basic understanding on WAAM and secondly to provide the logic to investigate further the deposition process, what it involves and which resources are consumed.

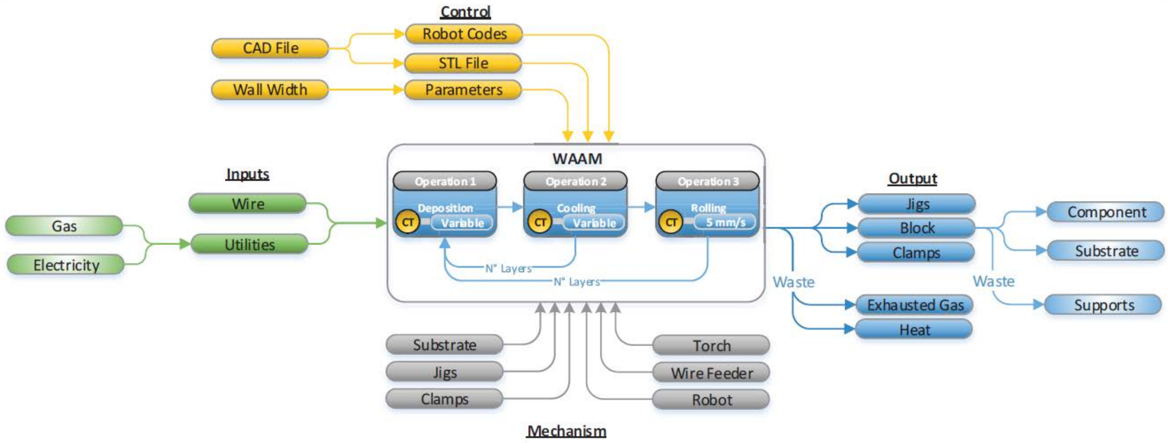


Figure 9 - Hybrid AM IDEF0

The inputs of a Hybrid AM system are mainly: standard wire, which ranges from 0.8 mm to 1.2 mm; and utilities such as gas to shield the deposition and ensure an oxygen free environment, and electricity to power all the elements of the system and to provide heat input for melting the wire. In some configurations there might be also cooling water which flows within the substrate to extract the excess heat from the component. On the operations side it is outlined that WAAM is broken down into three main phases: the deposition where the wire is melted to the desired shape, the cooling stage to reach optimal temperature and the milling phase to achieve a net-shape component. The mechanism of WAAM are the previously described torch, wire feeder and robot and the substrate which is the main building platform on which the deposition occurs, the jigs which are used to fix the substrate to the WAAM system and the clamps which are used to limit the distortion of the deposited material. The substrate, jigs and clamps need to be designed and customized based on the geometry of the deposition and they are utilizable for more depositions therefore they are represented also as outputs. The control side is made of a CAD file, which contains the geometry, and the process parameters file which controls some aspects of the generator, the robot and the wire feeder. Process parameters are extensive and are strongly linked with the quality of the material deposited. Main parameters are wire feed speed, travel speed, wall width, current, torch angle and trim. Controls are the most important and complex part of the WAAM system. Data processing activities allows converting CAD file containing the geometry, process parameters and building strategy into a readable robot program which controls the WAAM system. The first phase of the software is slicing the CAD file into Isoline paths, which needs to be converted into ASCII format in order to be processed by the Robot Control. Concurrently a Process Algorithm generates process parameters file.

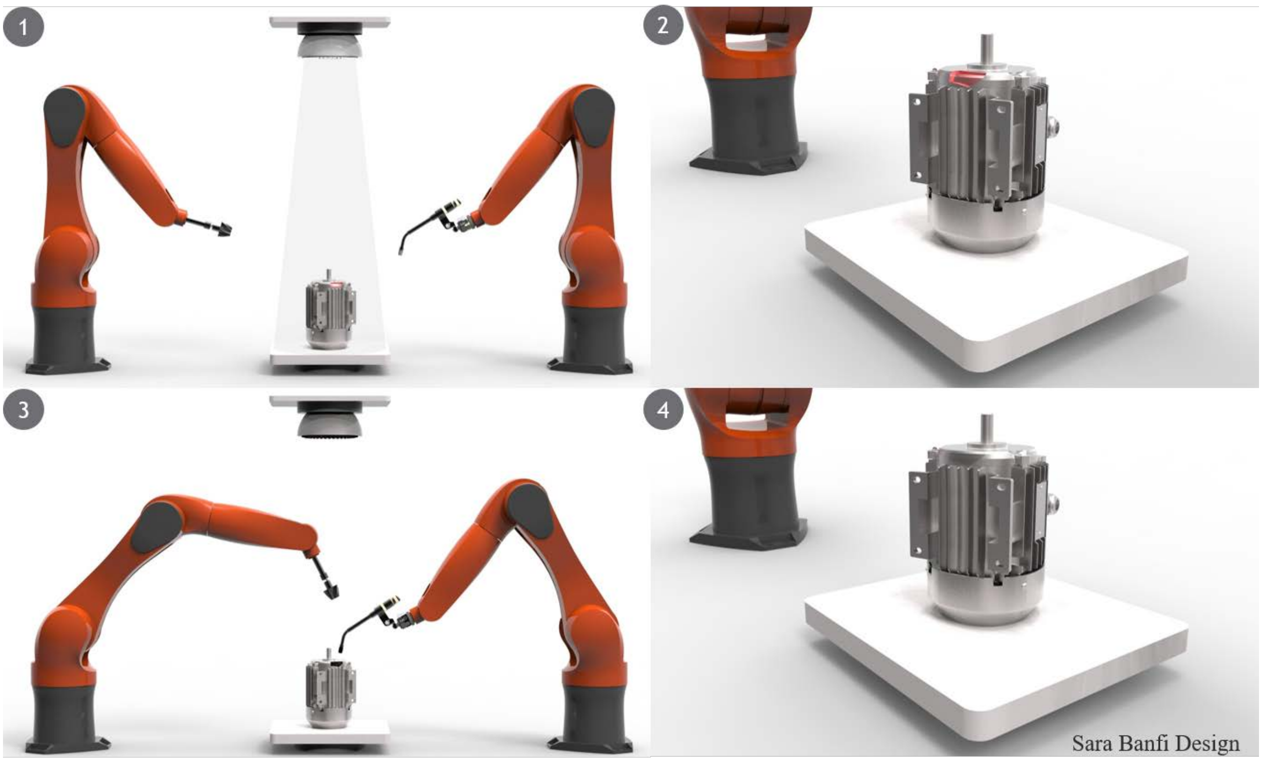


Figure 10 - Concept of Operation

The concept of operation of the Hybrid AM system is outlined in Figure 10 and consists of four main phases: 1) Failed component is placed within the system. 3D Scanner acquires geometric features 2) Software tool compares acquired geometry with original geometry and performs damage analysis and automatically develops robot codes for repair 3) Robots deposit a near-net shape volume of material; milling to remove the excess material and achieve a net shape geometry restoring the component. 4) 3D Scanner performs a tolerance test to ensure quality. The fully Integrated, deployable, Hybrid AM system outlined it Figure 10 is sided by a Human Machine Interface, CAD File Database, 3D Scanner. The system allows the deployment in the front- end of a support service system to print critical to availability metal components, when required. The Systems is intended primarily to repair broken components but can be employed to print new one. The capability delivered is *In-Field rapid manufacturing for repairs*. The system provides rapid response to supportability requirements of equipment and has a major impact when the aim is to support defensive platforms deployed abroad.

6.0 AM - DECISION SUPPORT SYSTEM

The Additive Manufacturing - Decision Support System (AD-DSS) is a software prototype, matured at Technology Readiness Level – 3 (TRL), which performs simulations for comparison of current military logistics with AM based logistics where AM systems are deployed in different stages of the supply chain (such as port, support vessels, forward bases or defence platforms). The AM-DSS is engineered for key decision makers of the NATO's Ministry of Defence to adopt a data driven approach for AM technology acquisition programs.

Figure 11 - Overview of AM - DSS

The AM-DSS is made of three different modules as outlined in Figure 11: 1) a logistic module where the user can input data on platforms, distances and locations, 2) an AM cost module where the user can select different AM technologies and perform a detailed product cost estimation and retrieve data on deposition time and 3) a simulation module where the user can select different System Configurations (SysCos) of the military logistic and perform a comparison of current and AM based supply chains.

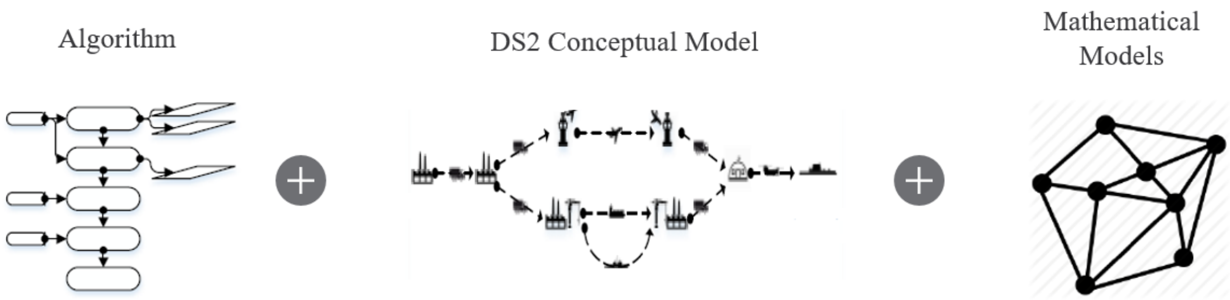


Figure 12 - AM-DSS Elements

The AM – DSS is comprised of four main elements outlined in Figure 12: 1) a novel algorithm to perform the comparison, 2) the conceptual model of a support service system, 3) mathematical models. These are also contributions to the body of knowledge of Systems Engineering.

Figure 13 - System Approach

The AM – DSS has been developed with a rigorous scientific method and is based on four peer-reviewed publications. Moreover, the system approach adopted for the development, has been published in the CIRP Procedia Journal and presented to the *CIRP Conference on Intelligent Computing* in 2017.

Through this system approach, the AM-DSS can be easily tailored to any organisation and AM technology with limited effort, providing accurate simulation results to the user. Moreover, with the user-friendly Graphical User Interface (GUI) and the Visual Interactive Environment (VIE) inexperienced users can execute the simulations through intuitions and deductions with limited training required.

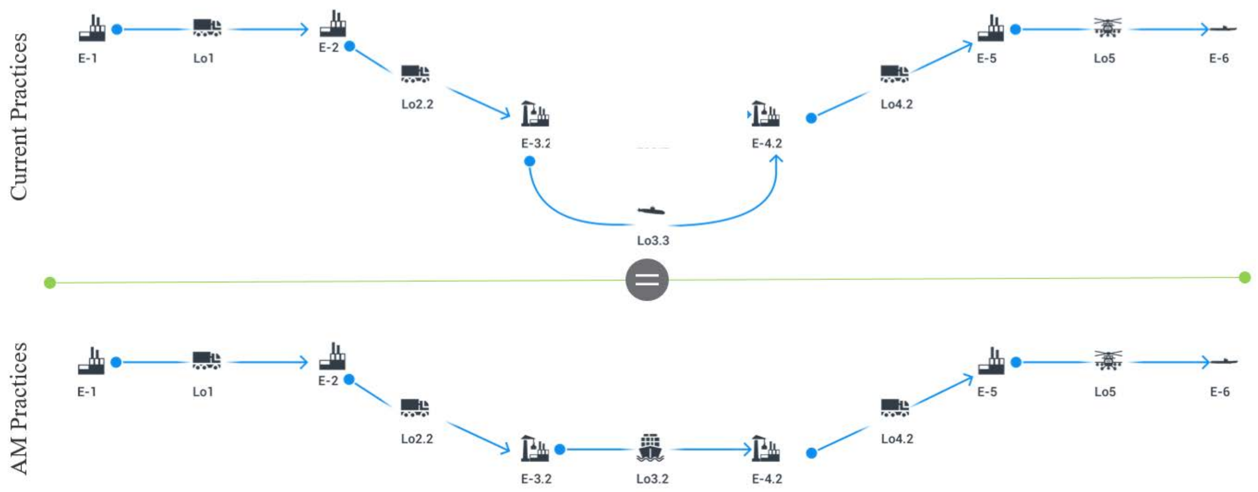


Figure 14 - Comparison of System Configurations (SysCos)

The AM - DSS can perform accurate and detailed product cost and lead-time estimations on components printed with AM and perform seven different simulations (SysCos) of forward deployments of AM systems. A visual representation of simulation is outlined in Figure 14 where a SysCo5 is compared with a SysCo4 in which the AM system is deployed in a Forward Base near the Battle Theatre. The output of the AM-DSS provides the user with data on Availability, Logistic Delay Time (LDT), Cost Breakdown Structure of AM printed components and Service Cost.

The AM - DSS includes four novel mathematical models on Wire + Arc Additive Manufacturing (WAAM), Fused Deposition Modelling (FDM), Selective Laser Melting (SLM) and a Hybrid WAAM system. The mathematical models of AM are based on a systematic literature review on AM technology and cost modelling techniques published in the *CIRP Journal of Manufacturing Science and Technology* in 2017. The mathematical models have been validated with leading AM organisations through case studies.

The other modules have been developed based entirely on primary applied research carried out with key players of the UK Defence Value Chain such as Babcock International, The Naval Command Headquarters (NCHQ), The Defence Equipment & Support (DE&S), The Defence Science & Technology Laboratory (DSTL) and finally the Ministry of Defence (MoD).

The current prototype version of the AM – DSS has been presented at the INCOSE conference *Conquering Complex Conundrums through Systems Engineering* in 2017, awarded the NATO - Defence Innovation Challenge in 2017, awarded the INCOSE Prize in 2017 and *Commended for Excellence* by the UK MoD. Finally, the AM – DSS scored 10 votes at the *Force Exploration Wargame* of the UK MoD in 2017.

6.1 Logistic Module

Module – 1, outlined in Figure 15 is used to model the whole military supply chain. It is based on the System of Interest (SoI) or conceptual model of a DS2 outlined in Figure 3 and is comprehensive of all System Configurations (SysCos) available to the MoD or DS2 provider to supply spare parts to the front-line.

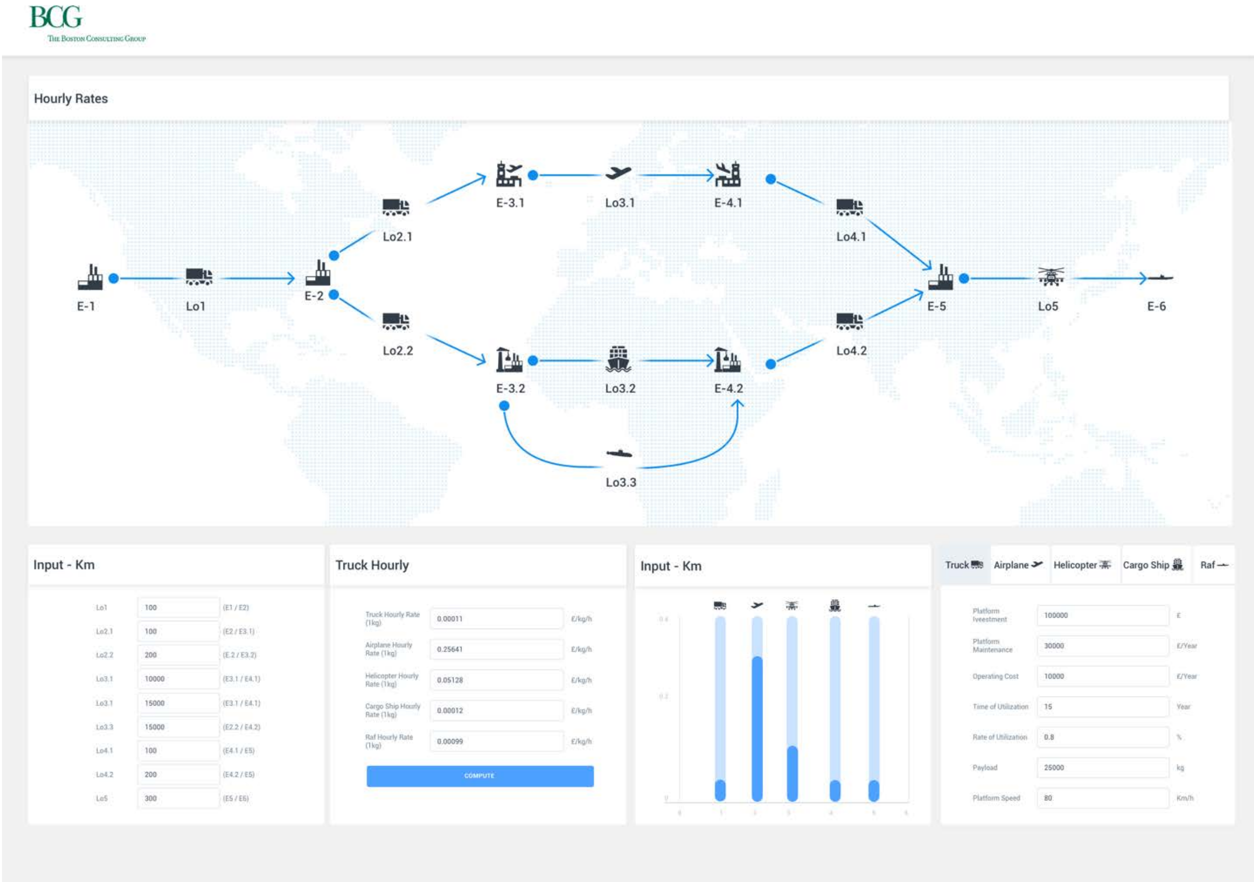


Figure 15 - Logistic Module

The SoI is a as Visual Interactive Environment (VIE) tool in order to provide the user with immediate information on System Elements, links, sequences and Logistic Platforms. A qualitative description on System Elements and Logistic Platforms is outlined in Appendix – 1.

Through this Module, the user can model easily the Logistic Platforms employed in delivering spares to the front-line such as trucks, airplanes, helicopters, cargo ships and support vessels. The user needs to input data on platform investment, yearly maintenance, yearly operating costs, time of utilization, rate of utilization, payload and average speed. Through these inputs, the Module is able to compute an hourly rate of each platform and visualise it in a graph.

Afterwards the user needs to input the distances (Km) between the System Elements, which varies, based on situation and current mission. An alternative approach is to employ the use of pop-up virtual maps as outlined in Figure 20 with drop pins, which automates the process.

Module – 1 has a total of 8 inputs of which 7 for the Logistic Platforms which may become default inputs and 1 on distances which changes per simulation. The outputs of the Module are 2, the logistic distances between System Elements and the Logistic Platform rates. The 2 inputs are sent automatically to Module – 3.

6.2 AM Cost Module

The Module – 2a & b are Additive Manufacturing Cost models developed using a system approach and based on Activity Based Costing (ABC) technique. The aim of the AM Cost Models is to estimate a detailed Cost Breakdown Structure (CBS) and outline performance indicators such as Cycle Time and deposition rate, the time for machining the printed component to achieve a net-shape. Moreover a library is included to simulate different materials such as Titanium, Aluminum Stainless Steel in case of the Hybrid AM system or polymers in case of the FDM system.

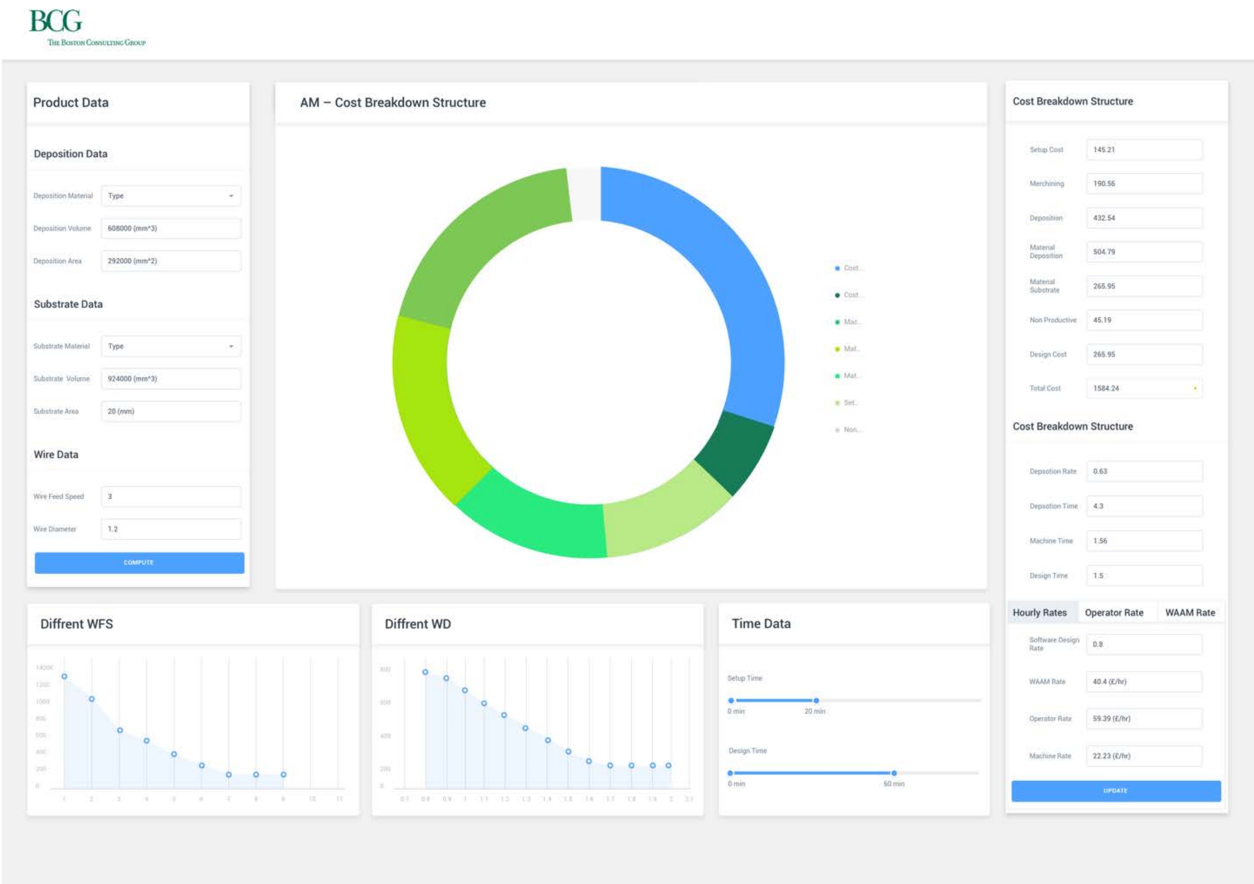


Figure 16 - Hybrid AM Cost Model

The user needs to input the product data, type of material (Aluminum, Titanium, and Stainless Steel), deposition volume of both the model and substrate, the deposition area and the substrate thickness. Moreover, the Wire Feed Speed (WFS) and the wire diameter have been included as these are variables of the process which have major impact on performance data. The module allows including the setup time and designing time, which in some situations may lead to high costs (i.e. in topology optimisation). Once the user fires the model, the results are displayed on the right side of the Graphical User Interface (GUI). These include a detailed Cost Breakdown Structure (CBS) with seven cost elements and a set of performance data such as the cycle time, deposition rate and design time.

Moreover, the mathematical model of machining allows to outline the time and cost to shift from a Near-Net Shape deposition to a Net-Shape one without the typical waviness of WAAM processes. Through the Tab-Box the user can model different types of Hybrid AM system, software and Milling robot. This feature makes the cost model highly flexible and allows the user to model different AM system configurations available on the market or tailor the cost model to different organization. Finally, the GUI displays two graphs, which plots two loops of different WFS and WD values to show the impact on cost.

The Fused Deposition Modelling (FDM) Cost Model outlined in Figure 17 can perform an accurate and detailed estimation of the process to deliver to the Royal Navy a plastic component printed with Fused Deposition Modelling (FDM). The Cost Model considers mainly three processes to deliver the component: 1) Bidding Process or Administrative Delay Time (ADT), 2) Design Process and 3) Manufacturing Process. This module does not include data on the logistics and simulates as SysCo - 1.

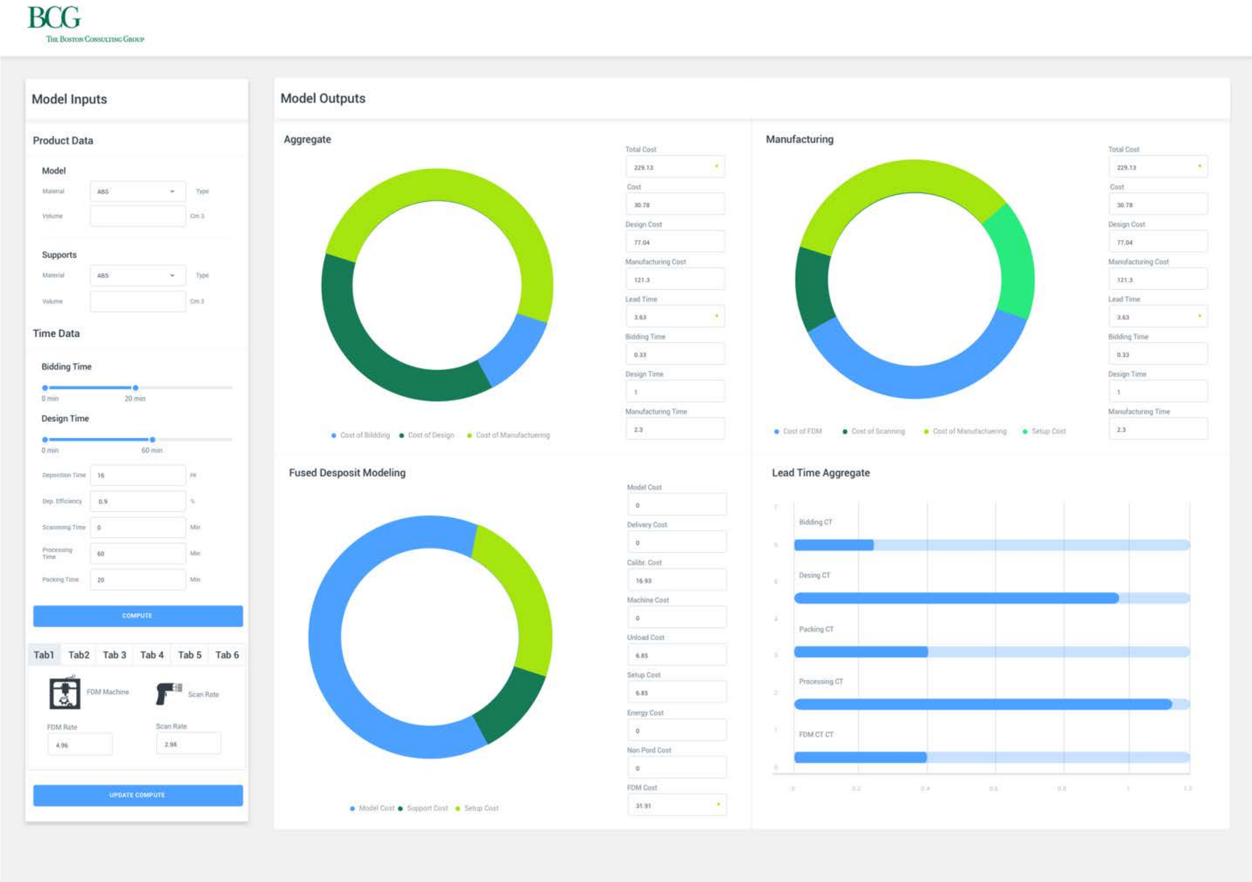


Figure 17 - FDM Cost Model

The user needs to select the polymer type of the component, input the volume of the component, the volume of the supports and substrate. Moreover, time data on design effort have to be included for re-design, optimisation and slicing activities as well as time for post-processing and 3D scanning for QA.

The output of the Module – 2b presents 15 cost elements which occur within an AM system which added together represent the Total Cost of the end-to-end process of delivering the plastic spare part to the Royal Navy. The cost to manufacture is made of the Fused Deposition Modelling (FDM) cost for printing the part, the Post-processing cost to obtain a finished part, the 3D scanner used for Quality Assurance to measure the physical tolerances of the part and finally the packing of the part for delivering it to the Royal Navy. The Cost Model is also able to estimate the cost and time of the bidding process or Administrative Delay Time (ADT) and geometry preparation process.

As for the Module – 2a, this module includes a Tab-Box to model the FDM, 3D scanner and software used in the process. This feature allows the user to adapt the model to other commercial version of these systems available on the market. The output of the models is the CBS of the printed component and is visualised within the module, furthermore the cost, AM cycle time outputs are sent to Module – 3. Finally, the cost models have been developed through primary research with leading AM R&D organizations and have been validated through case studies to verify their accuracy.

6.3 Simulation Module

Module – 3 is used to perform the cost/benefit analysis and provide the user with a user-friendly environment to simulate and compare traditional military supply chain options with AM supply chain, where AM is delocalized in different locations such as: port, support vessel, forward base and defence platform.

Figure 18 - Simulation Module

The simulation module is divided in three main sections: 1) Simulation Inputs, 2) Current Practices where Outputs of the traditional supply chain are displayed and 3) Next Generation Practices where outputs of the AM based supply chain are displayed. This type of structure allows the user to perform a data driven comparison of current and next generation practices and perform different simulations of System Configurations. The module has a Visual Interactive Environment (VIE) on the top part to display the SysCo selected through the ComboBox in the Inputs section. The user needs to select the System Configurations of both current and next generation practices and the location of the AM system. Moreover, data on Mean Time Between Failures (MTBF), Administrative Delay Time (ADT) and Procurement Delay Time (PDT) must be defined. In case of the next generation solution (AM based), the PDT is eliminated and substitute with the Cycle Time of the AM system. The AM - DSS performs automatically the calculations and provide the user with the following key performance indicators as outputs: Availability, Travel Times, Service Cost.

The module performs static and deterministic simulations but randomness can be easily modelled with pseudo-random generators. Given that Defence Support Service (DS2) systems are complex, stochastic system further work should be done to develop the AM-DSS into a dynamic and stochastic software tool. Failures of components can be modelled with Uniform distributions, availability of spares within the supply chain can be modelled with Boolean logic and Logistic Platforms' travel times can be modelled with Triangular distributions. Furthermore, a CNC machining module could be integrated.

7.0 CONCLUSIONS AND FUTURE WORK

This paper presented the AM-DSS applied research program. The paper contributes to the NATO-STO by introducing three contributions. Firstly, the System of Interest (SoI) of a Defence Support Services (DS2) system is described providing details on its System Elements, System Dynamics and System Configurations. Secondly, a Hybrid AM System for forward deployments in presented and described providing details on its IDEF0 and Concept of Operation. Thirdly, the Additive Manufacturing – Decision Support System (TRL - 3) is presented outlining its mathematical model (included in Appendix), development approach, constituent elements, modelling technique, simulation options and simulation types.

The AM - DSS is a cloud based, software platform, which allows users to perform simulations and cost benefit analysis of the deployment of different AM technologies in different stages of a military logistic. The software allows the users to compare a traditional military logistic where stocks are held in various stages (manufacturing occurs at the supplier's facility) with AM military logistics, where manufacturing can occur at a port, a support vessel, a forward base or the defence platform through deployable AM Systems. The AM - DSS can perform accurate and detailed product cost and lead-time estimations on components printed with AM and perform seven different simulations (SysCos) of forward deployments of AM systems. Given that, Defence Support Service (DS2) systems are complex, stochastic systems further work should be done to develop the AM-DSS into a dynamic and stochastic software tool. The aim of the AM-DSS program is to develop a mature and fully functional AM-DSS software to support NATO's MoDs in adopting a data driven approach in AM technology acquisition programs.

8.0 REFERENCES

Adebayo, A. (2014). Effects of solid lubricants on wire and arc additive manufactured structures. *Journal of Engineering Manufacture*.

Apte, A., & Rendon, R. (2009). A Diagnostic Approach to Weapon SYstem Lifecycle Support: The Phalanx Close-In Weapon System. *International Journal of Defense Acquisition Management 2.*

ASTM. (2013). *Standard Terminology for Additive Manufacturing Technologies* (No. F2792–12a). ASTM International.

Busachi, A., Erkoyuncu, J., Colegrove, P., Drake, R., Watts, C., & Martina, F. (2016). Defining Next-Generation Additive Manufacturing Applications for the Ministry of Defence (MoD). *Procedia CIRP*, *55*, 302–307. https://doi.org/10.1016/j.procir.2016.08.029

Busachi, A., Erkoyuncu, J., Colegrove, P., Drake, R., Watts, C., & Wilding, S. (2017). Additive manufacturing applications in Defence Support Services: current practices and framework for implementation. *International Journal of System Assurance Engineering and Management*.

Busachi, A., Erkoyuncu, J., Colegrove, P., Martina, F., & Ding, J. (2015). Designing a WAAM based manufacturing system for defence applications. In *Procedia CIRP* (Vol. 37).

Busachi, A., Erkoyuncu, J., Colegrove, P., Martina, F., Watts, C., & Drake, R. (2017). A review of Additive Manufacturing technology and Cost Estimation techniques for the defence sector. *CIRP Journal of Manufacturing Science and Technology*. https://doi.org/10.1016/j.cirpj.2017.07.001

Chen, J. (2012). *Hybrid Design based on Wire and Arc Additive manufacturing in the Aircraft Industry*. Crnafield University.

Colegrove, P. A., Coules, H. E., Fairman, J., Martina, F., Kashoob, T., Mamash, H., & Cozzolino, L. D.

(2013). Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling. *Journal of Materials Processing Technology*, *213*(10), 1782

Ding, J., Colegrove, P., Mehnen, J., Ganguly, S., Sequeira Almeida, P. M., Wang, F., & Williams, S. (2011). Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts. *Computational Materials Science*.

Hopkinson, N., & Dicknes, P. (2003). Analysis of rapid manufacturing—using layer manufacturing processes for production. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *217*(1), 31–39. https://doi.org/10.1243/095440603762554596

Ivanova, O., Williams, C., & Campbell, T. (2013). Additive manufacturing (AM) and nanotechnology: promises and challenges. *Rapid Prototyping Journal*, *19*(5), 353–364. https://doi.org/10.1108/RPJ

Iwata, C., & Mavris, D. (2013). Object-Oriented Discrete Event Simulation Modeling Environment for Aerospace Vehicle Maintenance and Logistics Process. *Procedia Computer Science*, *16*, 187–196.

Khajavi, S. H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in Industry*, *65*(1), 50–63. https://doi.org/10.1016/j.compind.2013.07.008

Lindemann, C., Jahnke, U., Moi, M., & Koch, R. (2012). Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing. *Solid Freeform Fabrication Symposium*.

Martina, F., Mehnen, J., Williams, S. W., Colegrove, P., & Wang, F. (2012). Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V. *Journal of Materials Processing Technology*, *212*(6), 1377–1386. https://doi.org/10.1016/j.jmatprotec.2012.02.002

MBDA. (2015). Missile systems, defence systems - MBDA missiles.

Pérès, F., & Noyes, D. (2006). Envisioning e-logistics developments: Making spare parts in situ and on demand. *Computers in Industry*, *57*(6), 490–503. https://doi.org/10.1016/j.compind.2006.02.010

QIU, X. (2014). E*ffect of rolling on fatigue crack growth rate of wire and arc additive manufacture (waam) processed titanium*. Cranfield University.

RAND. (2013). *Future Technology Landscapes*. Cambridge: RAND Europe.

Ruffo, M., Tuck, C., & Hague, R. (2006). Cost estimation for rapid manufacturing - laser sintering production for low to medium volumes. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *220*(9), 1417–1427.

Sabaei, D., Busachi, A., Erkoyuncu, J., Colegrove, P., & Roy, R. (2017). Defence Support Services for the Royal Navy: The Context of Spares Contracts, 459–470.

US Army. (2015). The Official Home Page of the United States Army | The United States Army.

Wang, F., Williams, S., & Rush, M. (2011). Morphology investigation on direct current pulsed gas tungsten arc welded additive layer manufactured Ti6Al4V alloy. *The International Journal of Advanced Manufacturing Technology*, *57*(5–8), 597–603. https://doi.org/10.1007/s00170-011-3299-1

Zhai, Y., & Lockett, H. (2012). Early cost estimation for additive manufacture.

APPENDIX – 1

Table 1 - SoI DS2 System Elements description

Tag	Description	Icon	Classification
E1	Suppliers		Static in safe environment
E2	Defence support service provider		Static in safe environment
E3	Royal navy port		Static, partially in safe environment
E4	Surface support vessel		Active, critical environment
E5	Defence platform		Active, critical environment (operational theatre)
E6	Defence platform		Active, critical environment (battle theatre)
E7	Forward base		Active, critical environment (operational theatre)
E8	Commercial vessel		Active, critical environment
E9	MoD		Static, partially in safe environment

Table 2 - DS2 SoI Logistics description

Tag	Reference	Icon	Description
L-1 or P1	E1–E2		Land transportation between suppliers/manufacturers of components and the DS2 provider
L-2	E2–E3		Land transportation between the DS2 provider and the port, owned and managed by DS2 provider and operated by Royal Navy
L-3	E3–E4		Port transportation between the warehouse and the surface support vessel
L-4	E4–E5		Sea transportation between the surface support vessel and the defence platform.
L-5	E2–E5		Air transportation between the DS2 provider and the defence platform
L-6	E3–E5		Port transportation between the warehouse and the defence platform
L-7	E3–E8		Port transportation between the warehouse and the commercial
L-8	E8–E7		Sea transportation between the Commercial vessel and the forward base
L-9	E2–E4		Air transportation between the DS2 provider and the surface support vessel

APPENDIX – 2

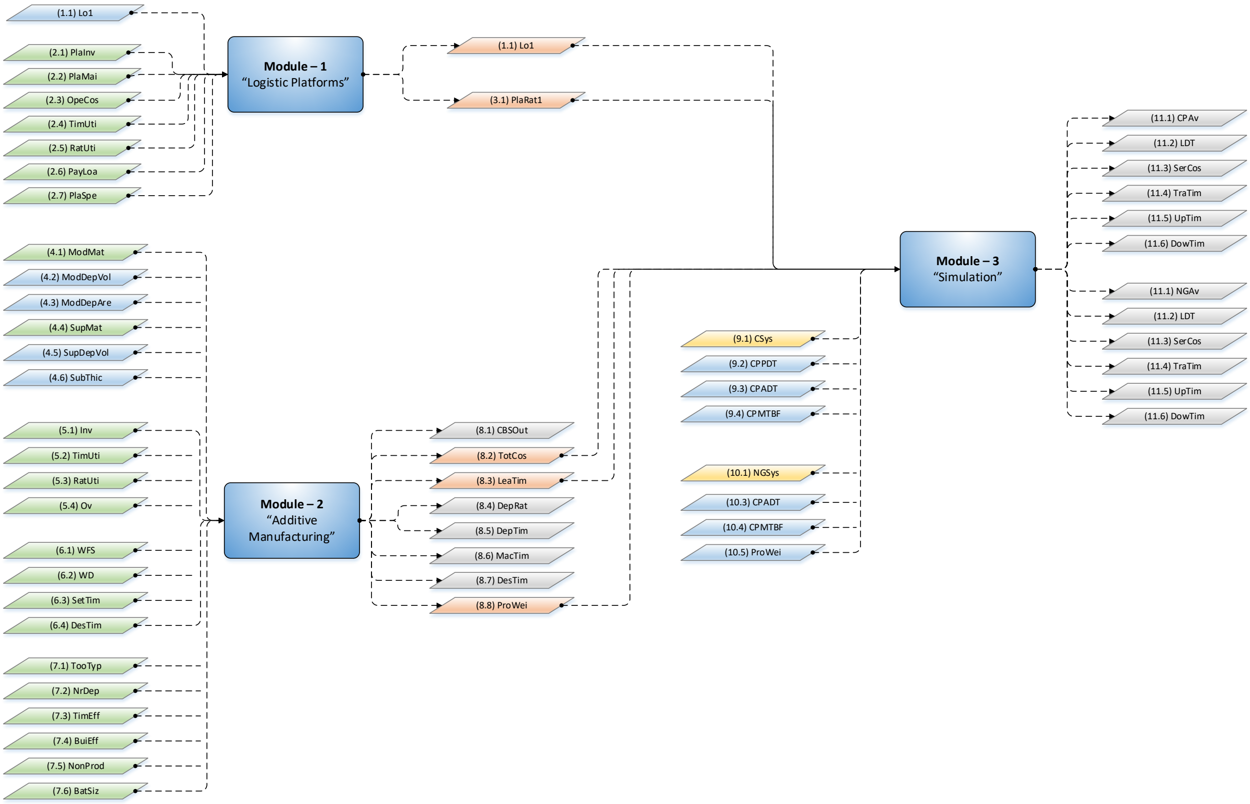


Figure 19 - AM-DSS Software Architecture

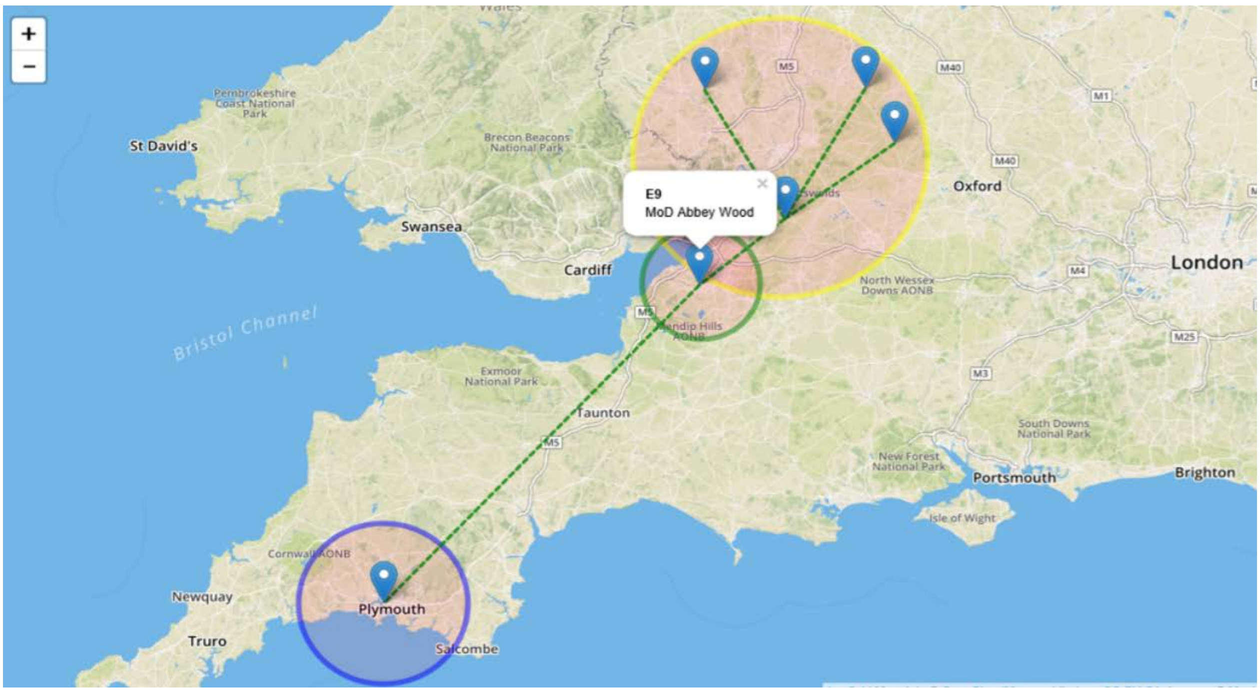
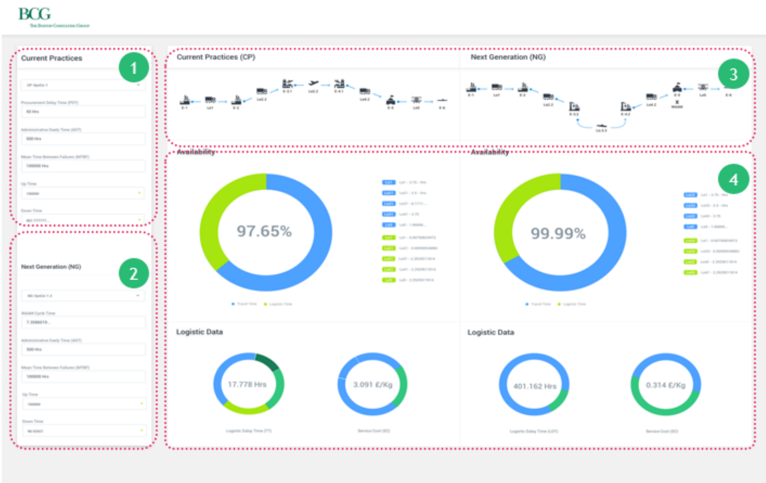


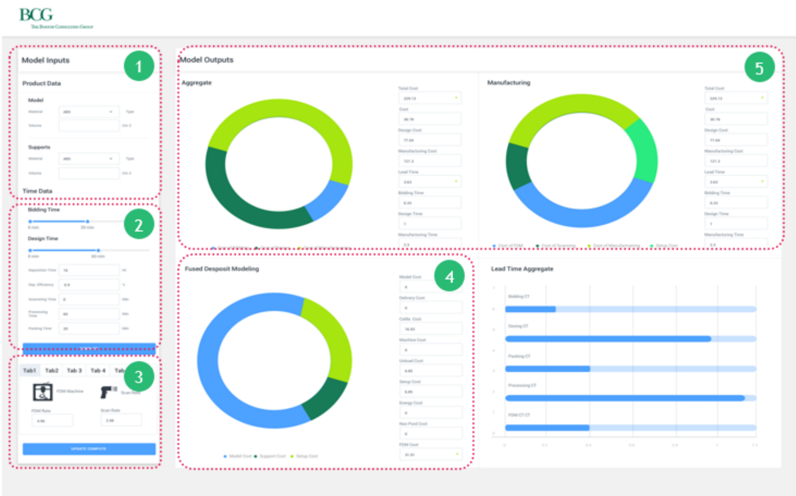
Figure 20 - Pop-Up Virtual Map

APPENDIX – 3



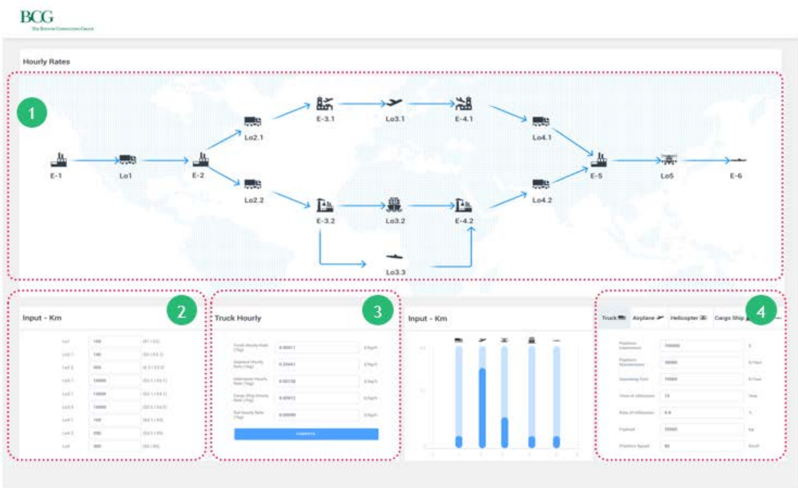
Module Description

1. Inputs of Current Practices: User needs to select System Configuration (SysCo) of current practices i.e. Air, Land and Sea supply options and inputs on PDT[1], ADT[2], MTBF[3].
2. Inputs of AM Practices: User needs to select System Configuration (SysCo) of AM practices i.e. Air, Land and Sea supply options and the location of the deployed AM system and inputs on ADT and MTBF. The AM Cycle Time is retrieved automatically from Module - 2.
3. SysCo[4] Visualisation: This helps the user to visualise instantly on the SysCo selection of current and AM practices.
4. Output Data and Visualisation: This is the part for the user to make the comparison. The outputs are Availability, LDT[5], LC[6] and are represented with pie-charts.



Module Description

1. Product Data Input: In this section the user can select the material of the component and input the volume of the product and the data on the substrate.
2. Additional Inputs: In this section the user can enter the time of design, 3D Scanning, Post-processing time and packing time.
3. FDM & 3D Scanning System Inputs: In this section the user can input data of the FDM machine and the 3D Scanner. This section allows the user to tailor the Cost Model to different organisations.
4. Cost Breakdown Structure: This is the module output and is made of 9 cost elements occurring during a deposition with FDM.
5. Aggregate & Manufacturing Cost: This section outlines details of other costs occurring in an AM based manufacturing System.



Module Description

1. System of Sinterest: This is the partial representation of the System of Interest (SoI) of a military logistic, sequences, platforms and System Configurations (SysCo) are represented.
2. Distances: This section is used to input the distances between the static elements of the SoI i.e. supplier, MoD, port, airport, forward base.
3. Platforms Rate: This is the output of the module which is an hourly rate of each platform employed in the military logistic.
4. Platforms Inputs: In this section the user can input data on the logistic platforms such as speed, investment, yearly maintenance, utilization rate and payload.

APPENDIX – 4

Table 3 - Experts from MoD and Industry Involved in Validation

Organisation	Type	Years of Experience	Position	Reference
"Ministry of Defence" (MoD)	Royal Navy	15	NAVY Eng Spt-Sup Sol SO1	CF + SoI
		10	NAVY MARCAP-ST LOGS AW PLAT	CF + SoI
		10	NAVY LOG INFRA-FUTURE CAP SO2	CF + SoI + CP
		5	NAVY LOG INFRA-FUTURE CAP SO3	CF + SoI
	NCHQ	30	Royal Navy Commander	CF + SoI + CP
		15	NAVY MARCAP - Manager	CF
		10	NAVY MARCAP –Manager	CF
	Defence Equipment & Support	5	DES TECH-TechOffice Maritime-RM	CF + SoI + CP
		5	DES TECH-TechOffice Maritime	CF + SoI + CP
		10	DES TECH-Tech Office Maritime	CF + SoI + CP
		5	DE&S Technology Office	CP
		10	DE&S Technology Office	CP
	DSTL	3	Navy Maritime Warfare Centre	CF + SoI + CP
Company – 1 (SME)	R&T AM	20	Chief Executive Office	AM + MM + CF
		15	Technical Lead	AM + MM + CF
		5	Project Design Engineer	AM + MM + CF
Company – 2 (Large)	DS2	15	Engineering Director	CF + SoI + CP + MM + AM
		20	R&D Manager	CF
		10	Principal Engineer	CF + SoI
		10	Technology Acquisition Lead	CF + SoI + CP + MM + AM
		20	Through-Life Support Manager	CF + SoI + CP + MM + AM
		20	In-Service Support Manager	CF + SoI + CP + MM + AM
Company – 3 (SME)	R&T AM	15	Chief Executive Officer	AM + MM + CF
		5	Project Engineer	AM + MM + CF
		10	Head - Advanced Manufacturing	AM + MM + CF
Research Centre	R&T	20	Senior Lecturer	CF + MM + AM
		5	Research Fellow	CF + MM + AM
		5	Senior Research Fellow	CF + MM + AM