CRANFIELD UNIVERSITY

ALESSANDRO BUSACHI

MODELLING APPLICATIONS OF WIRE + ARC ADDITIVE MANUFACTURING IN DEFENCE SUPPORT SERVICES

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING SYSTEMS ENGINEERING

PhD
Academic Year: 2014 - 2017

Supervisor: Dr. John Erkoyuncu, Dr. Paul Colegrove
JUNE 2017

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This thesis is submitted in fulfilment of the requirements for the degree of PhD

ABSTRACT

Current technological developments in "Additive Manufacturing" (AM) have increased confidence in the disruptive potential of this technology. Leading organisations in Industrial Product-Service System's (IPS2) are increasingly investing in R&D activities to better understand AM, its limitations and how to benefit now and in the future from its potential. AM capability acquisition may represent a source of competitive advantage and a means to develop new sources of income.

This PhD contributes to the current research effort on "AM applications in Defence Support Services" (DS2) for Royal Navy's platforms by providing significant evidence on the benefits of deployed AM. This PhD aims at developing a framework to assess costs and impact on availability of Additive Manufacturing applications in Support Services.

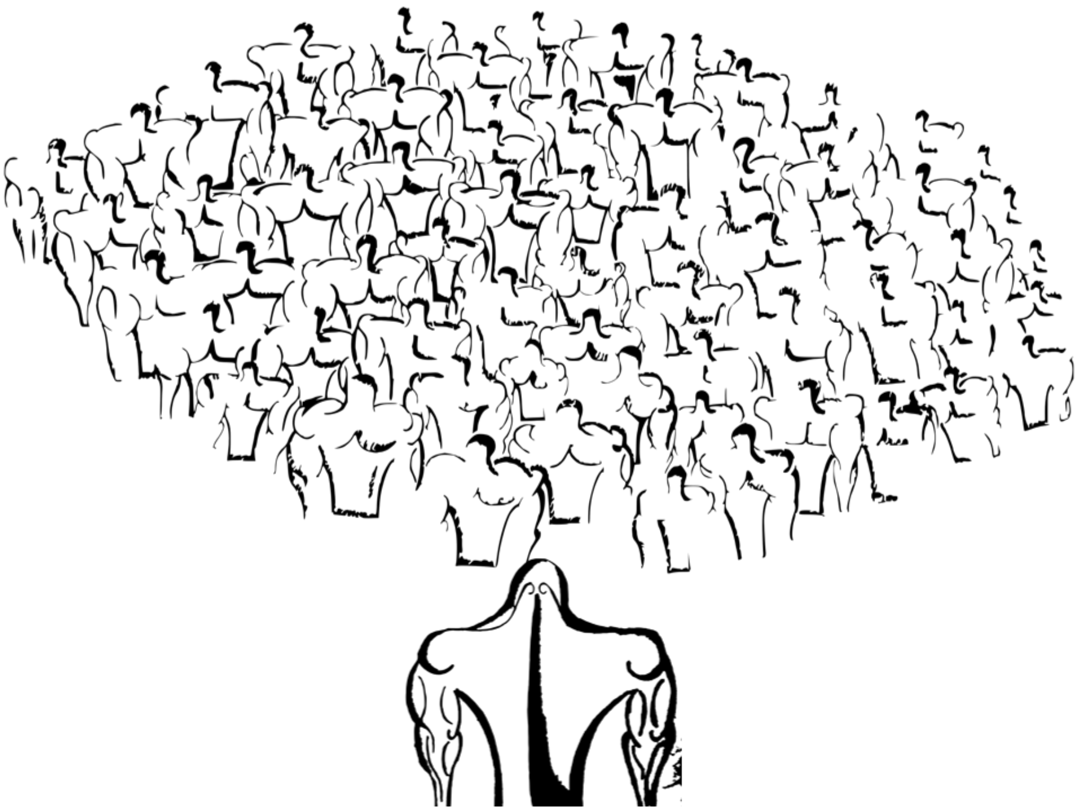
This PhD's contribution to knowledge is represented by the "System of Interest" (SoI) of a DS2 which defines its boundaries, links and elements, a Conceptual Framework for Additive Manufacturing assessment into DS2, Mathematical Models for estimating the Time and Costs of Additive Manufacturing considering the end-to-end process of delivering and printing an AM component, a Conceptual Framework to assess the Cost, Time and Benefits of AM and a Decision Support System for Additive Manufacturing applications in DS2 which allows to perform static and deterministic estimations on AM applications in the context of Defence Support Services. The main advantages of AM applications in DS2 are to provide platforms with the ability to sustain their systems, recover its capability after damage, solve obsolescence issues and collapse dramatically the supply chain.

Keywords:

Defence Support Services, Additive Manufacturing, Decision Support Systems

ACKNOWLEDGEMENTS

I would like to extend my gratitude to my supervisors Dr John Erkoyuncu and Dr Paul Colegrove for their support during these years. I have grown professionally and personally during my PhD and this is mainly due to their stimulus. I would like to thank also Dr Chris Watts and Dr Richard Drake of Babcock International, their industrial experience, coupled with their scientific mind-set provided me an invaluable input to my PhD. Finally, I would like to thank also my friend and colleague, Dr. Filomeno Martina and absolutely no one else. Only we know what we went through.



"Ardito, Infiammami il Cuore con il tuo Incredibile Slancio, con il tuo Altissimo Ardimento, con la tua Lucente Onestà. Riversami di Passione e Orgoglio"

(Busachi, 2018)

LIST OF PUBLICATIONS

Journals

Busachi, A., Kuepper, D., Brunelli, J., Heising, W., Moeller, C., Fisher, D., Drake, R. (2018). Additive Manufacturing – Rapid Support System (AM-RS2): Concept Design of a deployable AM unit for War Theatre. *NATO STO*, 1–20. https://doi.org/10.14339/STO-MP-AVT-267-03A-PDF

Busachi, A; Kuepper, D; Brunelli, J; Heising W.; Moeller, C.; Fisher D.; Watts, C.; Drake, R. (2018). "Modelling Applications of Additive Manufacturing in Defense Support Services." *NATO STO*, 1–23. https://doi.org/10.14339/STO-MP-AVT-267-03B-PDF

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 defense sector. *CIRP Journal of Manufacturing Science and Technology*, *19*, 117–128. https://doi.org/10.1016/j.cirpj.2017.07.001

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Conference Papers

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

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Book chapter

Sabaei, D., Busachi, A., Erkoyuncu, J., Colegrove, P., & Roy, R. (2017). Defense Support Services for the Royal Navy: The Context of Spares Contracts (pp. 459–470). https://doi.org/10.1007/978-3-319-49938-3_28

Awards and Research Impact

Appointed by the "Defence Science & Technology Laboratory" (DSTL – MoD) to the NATO AVT – 267.

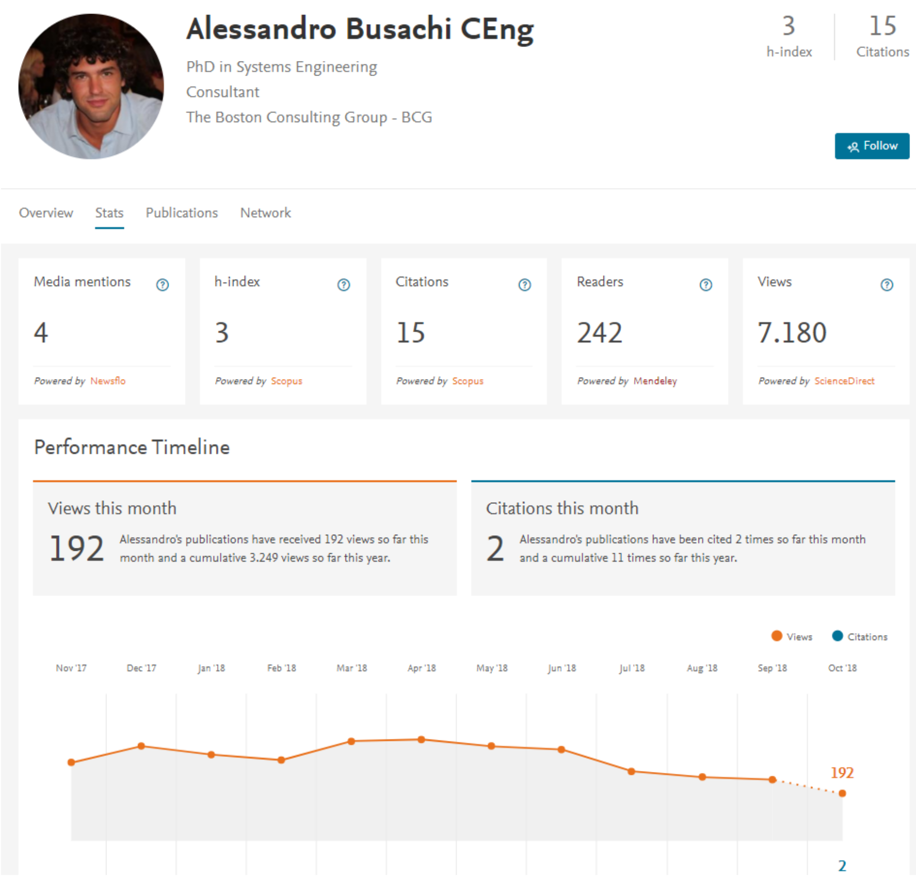
Awarded the "NATO – Defence Innovation Challenge" in Berlin, Germany in April 2018, by the North Atlantic Treaty Organisation (NATO).

"Commended for Excellence" by Team Defence – UK MoD, Defence Academy Shrivenham, in April 2018.

"Commended for Excellence" by the UK Council of Electronic Business (UKCeB) – UK Defence Academy, Shrivenham, in April 2016.

Awarded the "NATO – Defence Innovation Challenge" in Ottawa, Canada, in April 2017 by the North Atlantic Treaty Organisation (NATO).

Awarded the Swiss INCOSE Student Prize 2017 in Zurich, Switzerland, September 2017.



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IT	Information Technology
DS2	Defence Support Service
DSS	Decision Support System
WAAM	Wire+Arc Additive Manufacturing
FDM	Fused Deposition Modelling
SLM	Selective Laser Melting
SysCo	System Configuration
OpEnv	Operating Environment
Lo	logistic
SE	System Element
SoI	System of Interest
MM	Mathematical Model
Av	Availability
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
LDT	Logistic Delay Time
ADT	Administrative Delay Time
IPS2	Industrial Product Service Systems
CfA	Contract for Availability
RN	Royal Navy
CES	Complex Engineering Systems
OEM	Original Equipment Manufacturer
ABC	Activity Based Costing
PDT	Procurement Delay Time
TIG	Tungsten Inert Gas
DED	Direct Energy Deposition
BPM	Business Process Mapping
BTF	Buy to Fly Ratio

1 Introduction, Research Aim and Objectives

1.1 Introduction

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 the "Additive Manufacturing – Decision Support System" (AM-DSS) a software tool, 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.

This PhD contributes to the current research effort on "AM applications in "Defence Support Services" (DS2) for Royal Navy's platforms. AM represents a disruptive technology in the Defence Support Service context. If AM is applied in the front-end of a support service the Logistic Delay Time (LDT) reduces dramatically therefore the availability increases.

Through a literature review and unstructured interviews with a leading Defence Support Service provider, it was possible to identify research gaps and industrial challenges on AM applications in DS2.

This lack of research leads to a wide knowledge gap, which must be addressed to reduce the barriers of AM adoption by DS2 providers. A general lack of data regarding design and engineering aspects together with the absence of comparison with traditional DS2 leads to a high degree of uncertainty. This leads to key industrial decision makers being reluctant to acquire AM capability. This PhD's contribution to knowledge is represented by 1) the "System of Interest" (SoI) of a DS2 which defines its boundaries, 2) a conceptual framework for Additive Manufacturing assessment into DS2, 3) mathematical models for estimating the time and costs of Additive Manufacturing, 4) a conceptual framework to assess the cost, time and benefits of AM and a Decision Support System for Additive Manufacturing applications in DS2.

1.2 PhD Aim and Objectives

This PhD focuses on the evaluation of Additive Manufacturing applications in the context of Defence Support Services. The PhD contributes to knowledge through development of a framework, which can estimate the cost, time and benefits such as impact on availability of AM applications in different locations of a Defence Support Service system.

The PhD aim is to develop a framework to assess costs and impact on availability of Additive Manufacturing applications in Support Services.

PhD Objectives:

- To review WAAM technology and cost modelling techniques
- To investigate current practices and define a System of Interest (SoI) of a Defence Support Service (DS2) using a system approach. This objective allows the definition of the boundaries, elements, links, sequences of a Defence Support Service.
- To develop a holistic conceptual framework to assess AM applications in Support Services. The framework defines the necessary phases required to perform the assessment.

- To develop a Decision Support System (DSS) to assess quantitatively the impact of AM applications in DS2 outlining estimate on cost, time and availability. The DSS is engineered for early stages of technology acquisition programs.

- To verify with dry runs the AM-DSS and validate the previous objectives with expert's judgement from academia and industry.

Research Stakeholders:

Ministry of Defence, Babcock International, Defence Equipment & Support

1.3 PhD Contribution to Knowledge

This applied research project provides increased understanding and evidence of Additive Manufacturing applications in the Defence Support Services (DS2) sector. Four novel and original PhD's developments contribute to the body of knowledge in Systems Engineering and Through-Life Engineering:

- The development of a "System of Interest" (SoI) of a DS2 which defines its boundaries, links and elements outlined in Chapter - 3

- The creation of a conceptual framework for Additive Manufacturing assessment in DS2 outlined in Chapter - 6

- The development of mathematical models for estimating the time and costs of Additive Manufacturing outlined in Chapter - 5

- The Decision Support System for Additive Manufacturing applications in DS2 outlined in Chapter - 8

Through the application of a hybrid approach (system approach and Activity Based Costing technique), the first three original contributions to knowledge have been merged into an innovative and significant "Decision Support System" (DSS) which can generate reliable, accurate and detailed estimates of AM applications into DS2. The DSS is a software prototype engineered for "Research & Development" (R&D) units employed in early stages of "Capability Acquisition" (CA) programs. The targeted capability which is investigated for acquisition is defined as follows:

” the capability to additively manufacture critical-to-availability components next/close to the point of use only when they are required, to maximise operational availability and reduce cost and time of Defence Support Services (DS2)”.

The Decision Support System is considered significant as it can be fed with data and improve the decision making of the R&D unit through the provision of evidence on where Additive Manufacturing can be applied within DS2, how to estimate the cost and time of both product and service, and finally how to evaluate the benefits of AM applications within DS2.

1.4 Research Problem

DS2 are complex “Industrial Product-Service Systems” (IPS2) which can deliver on a turn-key basis equipment, training, technical support, spare parts, platforms, supply chain management, project management, people, revamping, upgrades, expertise and know-how. DS2 are required to be highly responsive, operate in mission and safety critical environments anywhere in the world and support complex engineering systems featured with advanced technologies. DS2 can be described as systems made of a wide range of elements featured with complexity, interconnectedness, uncertainties and variability. They have a dynamic and stochastic nature featured with randomness which implies complex dynamics. The states of the system must be determined probabilistically and the behaviour must be observed over time (i.e. 30 years). AM applications in Defence Support Services may provide precious advantages in terms of time, cost and availability of systems giving both the service provider and the Ministry of Defence (MoD) cost and strategic advantages. AM based DS2 differentiate themselves from traditional DS2 mainly due to their ability for delocalised manufacturing of any kind of geometry. Manufacturing can occur within a port, a support ship or a defensive platform such as an aircraft carrier or a destroyer. This is possible through a robust and autonomous manufacturing system based on AM, which merges together equipment, people, software and competencies. The mission of an AM system is to support engineering systems which are under “Contracting for Availability” (CfA), which the aim is to maximise “availability” through the rapid manufacture of any type of spare part required by the engineering system to operate and deliver its capability. Moreover, having manufacturing capability on-board, allows the platform to recover its structure aftershocks providing a strategic advantage and improving survivability metric. This PhD addresses the uncertainties, due to a lack of research, of Additive Manufacturing applications in the context of Defence Support Services. The uncertainties are given by lack of data on time, costs and benefits of deployed AM in the front end of a Defence Support Service.

1.5 The Royal Navy's Challenge

In recent years "Her Majesty's Government" (HM Gov.) outlined in the "National Security Strategy" the main objectives of the "Ministry of Defence" (MoD) for the next years of operation. The objectives are summarised as: 1) to protect our people, 2) to project our global influences and 3) to promote our prosperity (HM Government, 2015). 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 (MoD, 2015). The budget is allocated mainly for platforms acquisition and support for air, land and sea applications. The entity in charge on acquiring and supporting the platforms is the "Defence Equipment and Support" (DE&S) which is part of the MoD. Between 2014 and 2015 the MoD and DE&S have been involved heavily with partners and directors of McKinsey a leading strategic consulting firm, technical consulting firms such as Atkins and Jacobs and finally chief executives of major armament manufacturer such as General Dynamics, Lockheed Martin and BAE Systems for planning MoD activities of the following 10 years. In 2015 the DE&S issued the "Defence Equipment Plan" providing information on how the £160 Billion budget will be spread (MoD, 2015).

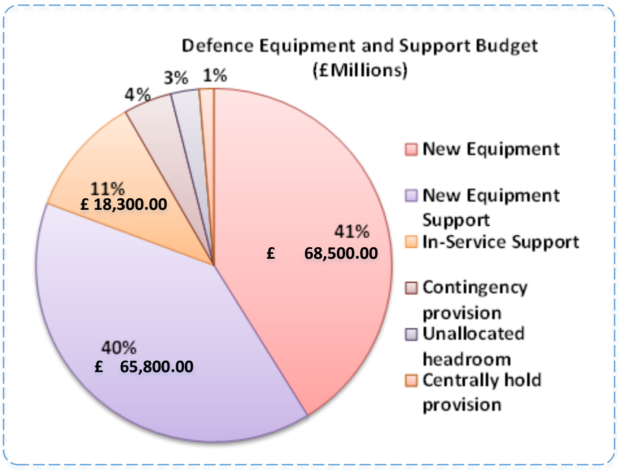


Figure 1 - DE&S Budget Breakdown

As outlined in Figure 1 - DE&S Budget Breakdown, £68,500 Million (41%) are 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 (MoD, 2015). 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 (DoD, 2014). Moreover, Figure 2 - DE&S Budget by Application 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).

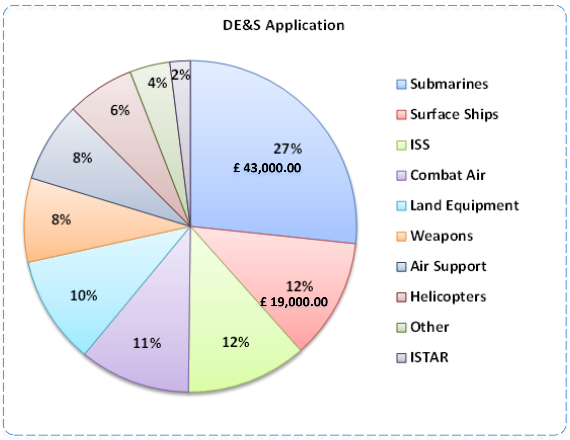


Figure 2 - DE&S Budget by Application

The budget of £61 Billion for Royal Navy is employed mainly for design, build, maintenance and acquisition and maintenance of on-board complex systems. According to MoD (2015) by 2025 the DE&S has to acquire and commission:

- 4 x SSBN Nuclear Deterrent subs
- 7 x SSN Hunter Killers subs
- 2 x Aircraft carriers
- 15 x Destroyers and Frigates
- 6 x Patrol vessels
- 3 x Support ships

The actual data of support activity cost for Royal Navy is not precisely know but a rough estimated shows that £800 Million are required to operate and support around 74 defence maritime platforms each year.

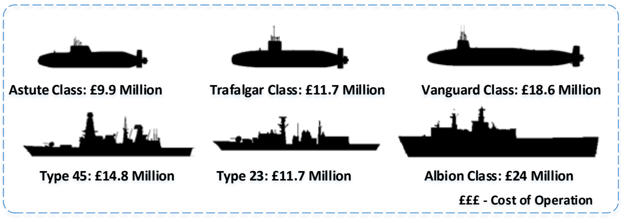


Figure 3 - Cost of Operation

In Figure 3 - Cost of Operation some data of yearly operating cost is outlined which includes only personnel, fuel, travels and port visits. The cost varies from a minimum of £9.9 Million for an Astute class submarine to a max of £24 Million for an Albion class surface vessel. 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.

- **Government pressure and budget cuts:** Government is increasing the pressure on MoD in order to improve its operations and lower its costs. HM Gov has increased the employment of strategic and technical consulting firms in the past years in order to develop performance improvement projects. MoD in strongly involved with McKinsey, Deloitte, PWC, Atkins, Jacobs in order to reduce its costs.

- **Increase of number of Platforms of the Royal Navy:** The MoD will increase its number of defensive platforms of the Royal Navy. Currently it holds 74 platforms and will acquire another 37 by 2025. With the increase in the number of platforms the support service becomes more complex and costs will increase consistently. It will require to expand its current team, operations and facilities.
- **Forecasting the demand of spares:** It is very difficult to forecast the demand of the spares required by a platform. This is mainly given by the extended number of components operating on the platforms and the unpredictability of random failures and inability to forecast the utilisation of the complex systems. Current strategy is to stock critical-to-availability components within the platform but unfortunately defence platforms are featured with space scarcity. Moreover components subject to failures and wear are purchased in advance and stored in warehouses in order to eliminate the procurement lead time.
- **Extended and disrupted supply chains:** Royal Navy platform may operate everywhere in the World and can be featured by extended and disrupted supply chains. In a battle theatre the platform is isolated and has to rely on internal resources in order to support its complex systems. Moreover extended supply chains results in high cost for delivery and long lead times.
- **Obsolescence of components:** Defence platforms are affected by obsolescence costs. It is widely reported that various component become obsolete before the platform gets commissioned. The main strategy of MoD for mitigating this risk is to acquire and stock large inventory of components in warehouses. This results in high costs. Also, when MoD runs out of spares it has to look for manufacturers which are willing to run the production of few batches resulting in high cost of product.
- **Delocalised Manufacturing in the front-end of a Defence Support Services:** Mini-factories can be developed within containers and deployed in forward bases in order to reduce the distance to the point of use of the components. This allows to eliminate the planning of components required (forecasted) and produce only what is actually required in the battlefield. Mini-factories can be

developed also for in-platform deployment which will eliminate the logistic delay time.

- **"Additive Manufacturing" (AM):** Additive Manufacturing (generic) is a disruptive technology which benefits from design freedom, short manufacturing lead times, low buy-to-fly (BTF) ratios, complexity for free and requires limited space for operating. AM can be used for both, printing new components and repair broken ones (if combined with machining and 3D scanner). AM has the potential to reduce or eliminate sub-assemblies, access to new geometries and improve the performance of components. AM production aspects is Lean, it benefits from "pull" and "just-in-time" moreover the technology can process random geometries without any impact on setups. AM can be deployed for components, humanitarian aid, tools, repairs, temporary replacement, prosthesis, embedded sensors, drones and consumables.
- **"Wire + Arc Additive Manufacturing" (WAAM):** WAAM is an AM technology which is not present in international standards but it is considered the most promising technology for industrial applications. Firstly it is a wire based technology which implies: no health and safety issues compared with powder solutions, easy material feed, medium cost of wire, and 100% material efficiency. Featured with high deposition rates (kg/h), low BTF ratios (2), low cost of investment (max £200k), high energy efficiency (90%), good accuracy (1-2 mm), low product cost and manufacturing lead times (hrs), deposition occurs out of the chamber with unlimited size constraints and lower space required, good design freedom and topological optimisation opportunity, good mechanical properties and microstructure (rolling) and no porosity.
- **Digital Supply chain:** Through the use of AM, there is a considerable transformation from a physical supply chain to a digital supply chain. The most important "input" of the AM machine is the robot code obtained by a CAD File. Moreover the physical supply chain is tremendously reduced in terms of complexity. Only the wire of different material is shipped with the required utilities and consumables.

- **Performance:** If current support service are compared with next generation support services (based on delocalised manufacturing through AM) an impressive increase of performance is achieved. A preliminary analysis has been carried out on the “Highly Mechanised Weapon Handling System” (HMWHS): typical procurement and shipping to Port time is 2688 hrs while the printing of the biggest component can be achieved in 21.5 hrs (printing within the platform).

The “Royal Navy” (RN) operates a vast number of defence platforms, today 74 and by 2025 around 37 new platforms will be acquired and commissioned (MoD, 2015). The platform’s operation and support activities accounts up to 70% of the total cost of ownership and are carried out by the RN technical department and by “Defence Support Service” (DS2) providers (DoD, 2014). The platforms have 3 operational stances: 1) deployed 2) operational but not deployed and 3) non-operational. Each of the stances require different levels of support activities some of which are carried out continuously as routine maintenance and require many consumables. The RN platforms interact with the external environment through a vast number of “Complex Engineering System” (CES) which are critical to the platform’s survivability and lethality. CES may be featured with advanced technologies and a vast number of components such as the “Highly Mechanised Weapon Handling System” (HMWHS) which is made of 17 sub-systems and 1,500 components. To support CES, technicians need to be skilled and trained and require special tools to operate.

Moreover the platforms are featured with space scarcity, which has to be partitioned between: 1) critical-to-availability components, 2) tools and consumables, 3) humanitarian aid 4) other smaller platforms 5) small arms, 6) unmanned vehicles and consumables for the crew which is the mainly limiting factor of a platform’s autonomy (Busachi et al., 2015). In order to keep platforms operational and its systems available to operate when required to do so, the RN and DS2 providers need to establish support service systems in order to provide the platforms what they require wherever they are in terms of location and operating environment (Busachi, et al., 2016). Support service systems are complex, costly and inefficient systems which operate through different challenging operating environments such as war theatres where hostile entities with firing power are present. The supply chain of the support service system may need to be patrolled during war to avoid disruption. Moreover, as the platforms are operating in the sea these supply chains may be disrupted also by adverse weather conditions. Another case of supply chain disruption is the battle theatre where a platform is actively engaging hostile entities, in this case the platform is isolated and cannot be supported. Furthermore in the battle theatre, platforms may be subject to battle damage which may compromise capability and structural integrity and there is no way to prepare for this (Busachi et al., 2016).

RN platforms are required to be highly responsive to operation tempo, therefore the platforms and the crew must be highly resilient to fast changing operational environments and missions. Based on mission type the platform must tailor its inventory level but in some cases this is not possible given the urgency of deployment implying the platform to have partial or limited resources to accomplish its mission. Moreover, in case the platform must operate in "new waters" the support service system may be unestablished adding more challenge to the support. Given the criticality of support activities to keep the platform operational, both the RN and DS2 use modelling tools to forecast in advance what will be required, when and where. Nevertheless, modelling the demand of 74 platforms requires an immense effort and highly complex modelling tools which may not be accurate enough (MoD, 2015). Also, accuracy of forecasted platform's demand is based on quality and detailed data of historical usage which is difficult to capture, store, classify and use. It must be outlined also that systems are continuously upgraded or replaced in which case there is no data available. Moreover, in case of war time the modelling effort becomes ineffective as the platforms behaviour is uncertain and dependent on hostile initiatives. Another important aspect is related with the long lifetime of the platforms, which may be required to operate for 50 years (MoD, 2015). "Original Equipment Manufacturers" (OEM) involved in the development and support of the platforms and their systems may go out of business, abandon the production of the systems or components due to new designs or technological advancement. This leads to obsolescence cost which affect dramatically the "Ministry of Defence" (MoD, 2015). Moreover, the platforms are subject to accident such as fire, floods, collisions or grounding which may compromise CES or structures. As for battle damage, there is no way to plan the required materials, components and structures necessary to recover capability.

To cope with the above environmental challenges, the Royal Navy and DS2 providers have put in place all the necessary mitigation strategies which on one side are the only possible solutions and on the other side are considered not responsive enough and costly. For example, components and spares are spread over the whole support service system to reduce the "Logistic Delay Time" (LDT), which has the highest impact on operational availability. Moreover forward bases and support vessels are deployed and supply chains are established and maintained in order to improve the support to the platforms (Busachi et al., 2016).

Supporting RN platforms and its CES is a critical and necessary activity featured with uncertainty, complexity and ambiguity. The platform's and CES's availability is put at risk by different random events which makes challenging the support activity. Required materials, tools, spares, critical-to-availability components, structures and consumables are highly dependent on unforeseen events which are difficult to predict or control. Moreover, it is impossible to store all the necessary materials within a sole platform due to space constraints. Given the nature of DS2 systems, the following Additive Manufacturing's (AM) benefits seems to fit very well: 1) compactness of technology making it deployable, 2) high deposition rates, 3) ability to process random geometries, 4) ability to print large, fully dense metal components, 5) low product cost.

1.6 Additive Manufacturing Opportunities

The key players of the UK Defence Value chain outlined the same vision on AM to be exploited for delocalisation of manufacturing near the point of use or in different stages of the "Defence Support Service" (DS2) system such as port, support vessels or forward bases. The vision of AM in DS2 are mainly: to print, next to point of use, critical-to-availability components in order to eliminate or reduce the "Logistic Delay Time" (LDT) and improve availability of “Complex Engineering Systems” (CES), to repair components and structures when battle damages or accidents occur and recover capability, to print low value consumables inside the platform in order to reduce some inventory (Busachi et al., 2016). Other applications outlined are, to use AM to solve obsolescence issues and for repairing castings. The NCHQ sees immediate application of AM to produce gaskets, pump impellers, wear rings, combustion ware, guards and blocks and special tools required during on-board repairs. AM technical benefits have been outlined such as design freedom, compactness of technology, physical supply chain complexity reduction, digital supply chain, delocalisation, concurrent deposition of different materials, ability to process metals, plastic, ceramics and electronics, re-design for enhanced functionality or efficiency, elimination of sub-assemblies, multi-functionality, mass customisation. These benefits are shared with different levels, amongst most of the available process methodologies such as Laser Cladding (LC), Wire + Arc Additive Manufacturing (WAAM), “Fused Deposition Modelling” (FDM), “Selective Laser Melting” (SLM). According to Busachi et al. (2015) the above AM process methodologies are the most promising in the future for the “Royal Navy” (RN) needs. Nevertheless, even if AM processes such SLM, FDM and LC have been already commercialised these are still immature and will improve dramatically in the future. Moreover, these are too problematic, not efficient, costly, not tailored to the RN needs. More specifically SLM is not suitable for short to medium deployments within containers or within a platform due to its sensitivity and lack of robustness to cope with critical environments (require stable temperature, humidity and no vibration), very long cycle times given by slow deposition rates and inability to cope effectively with design complexity. SLM machines need to be calibrated every time they are subject to movements, moreover calibration takes up to 3 days. Furthermore, the powder bed nature of SLM makes its ineffective in vibrating and oscillating environments. WAAM process, even if still not matured till commercialised, is based on “Gas Metal Arc Welding” (GMAW) i.e. “Tungsten Inert Gas” (TIG), “Metal Inert Gas” (MIG) and Plasma welding and industrial robots are used for controlling the deposition. WAAM has an extended number of benefits. The 3 most important benefits of WAAM are 1) reliability, maturity and proven repeatability of its sub-technologies, 2) very high deposition rates with related low CT and 3) stability of arc + wire solution during vibrations and oscillations of platform. Nevertheless, WAAM is still under development at Cranfield University and cannot be considered user friendly as it needs a large amount of know-how and expertise to be operated.

Furthermore, AM operation aspects have been outlined. These AM operations aspects are based on "Manufacturing System Engineering", "Lean Manufacturing" principles and "Lean Product and Process Development" and are possible due to the delocalisation of AM production next to the point of use and through the involvement of the end-user:

- AM as an enabler of "Continuous Improvement" in the work place: RN operators, while deployed carry out their daily activities (with standard tools, jigs, equipment and kits) through which they mature a direct experience. During this experience, they might develop/generate ideas to improve a process. If a platform has manufacturing capability based on AM they can convert ideas into functional products.

- AM is an enabler of design freedom; it can print rapidly many kind of geometry without the need to setup the machine or change tools: this aspect fits very well if we consider that AM is deployed in a platform to "serve" various "Complex Engineering Systems" (CES) made of an extended number of components which all differ one from another in terms of geometry. A sole AM machine can manufacture all the components when these will fail.

- AM as an enabler of improved Product Development (PD): like the first point, AM allows to improve the Product Development. End-users, through the utilisation or direct experience develop/generate naturally ideas to improve their daily routine. AM as an enabler of CI is given by a combination of delocalisation of manufacturing next to the point of use, involvement of end-user (which detain the direct experience) in the PD and rapid prototyping capability to test the designs in the early stage.

- AM as an enabler of "Just-in-Time" (JIT): Considering the delocalisation of manufacturing within the platform, the "Logistic Delay Time" (LDT) is eliminated or dramatically reduced, moreover AM allows to achieve short CT of production. This combination allows to establish JIT principles which allows to reduce the stocks of finished goods and produce only the components that are required, when these are required.

- AM as an enabler of mass customisation: AM allows to produce highly tailored products to end user needs and unique features. This aspect is fundamental when special tools to perform an operation are required, when prosthesis needs to be tailored to the human body unique features or to provide special tools/small arms/body armours to soldiers.

2 Literature Review

2.1 Introduction

The scope of the literature review is to investigate three main areas "Additive Manufacturing" (AM) technologies, cost modelling techniques adopted for AM and availability of systems.

Firstly a general definition of AM has been provided, a "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). Then an IDEF0 of AM has been investigated and outlined, providing more details on what are the inputs, outputs, mechanism and controls of the process. Following an analysis of the ASTM (2013) and Martina (2014) classifications have been carried out. This allowed identification of suitable process methodologies for Defence Support Service System implementation. "Powder Bed Fusion" (PBF) and "Direct Energy Deposition" (DED) are considered the most promising and applicable process methodologies for industrial applications. DED is considered more applicable to large scale components where width of wall is minimum 1 or 2 mm. PBF is more applicable to complex functional components which require a high degree of accuracy.

Martina (2014) classification outlines also the categorisation by energy sources such as laser beam, electron beam and arc and feedstock type such as wire, blown powder and powder bed. This allowed it to include two more technologies, which are "Wire+Arc Additive Manufacturing" (WAAM) and Laser Cladding which is suitable for coatings and repairs. After identifying the suitable process methodologies, a more detailed analysis has been carried out at the technology level. For "Powder Bed Fusion" (PBF) two technologies have been investigated, "Selective Laser Melting" (SLM) and "Electron Beam Melting" (EBM). For "Direct Energy Deposition" (DED) three technologies have been investigated "Wire+Arc Additive Manufacturing" (WAAM), "Electron Beam Additive Manufacturing" (EBAM) and Laser Cladding.

The second part of the literature review focuses on cost modelling techniques. Firstly, an overview of current estimation techniques has been carried out. Following this a detailed review on cost modelling for AM has been investigated. The main finding is the application of "Activity Based Costing" (ABC) to cost modelling of AM. This is due to its ability to provide robust estimates and spread manufacturing overheads to targeted activities. Additionally, ABC does not require a wide range of historic data and a reliable model can be developed through interviews, observation and deduction. This technique has been adopted by Ruffo & Hague (2007), Ruffo et al., (2006), Lindemann (2012), Hopkinson & Dicknes (2003) and Zhai (2012). The approaches of the different authors are similar, they all break down the manufacturing process outlining all the activities involved in the deposition process and allocate a time and rate of machine, equipment and operators. Their findings are concerned with product cost and outlined that for PBF components major cost driver is the machine; this is due to slow deposition rates and high investment costs for the machine. In the case of DED the major contributor to cost is the raw material but a comparison with a traditional subtractive process outlined that there is a major cost saving due to higher material efficiency.

The third part of the Literature Review is concerned with outlining economic aspects of AM. This part of the review helps a better understanding of the technology and to outline details on where the technology provides a competitive advantage. The first finding is that AM does not benefit from economies of scale but provides complexity for free (no need for extra processes for complex geometries) and allows random processing of different geometries without affecting costs and times. This may lead to the conclusion that AM is particularly suitable for high value components with enhanced functionality in small to medium volume productions with the ability to provide high customization. The second finding is related to material efficiency and low Buy-to-Fly ratios. This leads to the conclusion that AM has a major advantage over subtractive manufacturing by providing better usage of materials. This aspect outlines the suitability of the technology for applications in Defence, Aerospace and Medical industries where advanced materials may reach high costs. Third finding is related with forecast of deposition rates which are promising as it is estimated that by 2023 SLM deposition rates may reach 80cm3/h.

The fourth and last part of the Literature Review is related with getting an understanding of how to measure availability of systems. The equation outlined that availability might be improved in two different ways. An internal way is the optimisation of the reliability of the component and the reduction of time to maintain. An external way is the reduction of the delivery time which is affected by the procurement delay and the supply of the part. As AM is an enabler of delocalised and rapid manufacturing it is concluded that the technology can optimise availability of systems through the in-field production of the component on demand. This PhD focuses on understanding benefits and barriers, of an AM implementation within Defence Support Services Systems for Royal Navy's platforms. This implies the design of the AM based system which is something that is missing in industry and academia. Therefore, there is a lack of data and knowledge which needs to be developed. To evaluate the implementation of AM within Support Services a comparison between traditional and AM based supply chains must be carried out and key decision variables such as lead times and Costs should be estimated. A link to availability has to be established as this is the key performance indicator to understand the profitability of the AM based system. This literature review helped to understand firstly AM technology, then which AM technologies are applicable to Defence Support Service Systems, outlines their performance envelope and identifies a suitable approach to system design and to perform the estimations of lead times and costs through interviews, observations and deductions. To obtain cost estimates an ABC technique will be utilised mainly for its ability to spread overheads and the ability to outline estimates when a physical system does not exist implying lack of historical data and knowledge. Moreover, this approach will allow the author to outline all the activities involved in the manufacturing system based on AM and its resource consumption. Resource consumptions play a major role as the technology might be utilised for In-Platforms applications implying a limited space and disrupted supply chains. This aspect outlines the requirement for autonomy.

2.2 Literature Review Methodology

This literature review covers three main central topics of the PhD included: 'additive manufacturing', 'cost modelling' and 'availability of systems'.

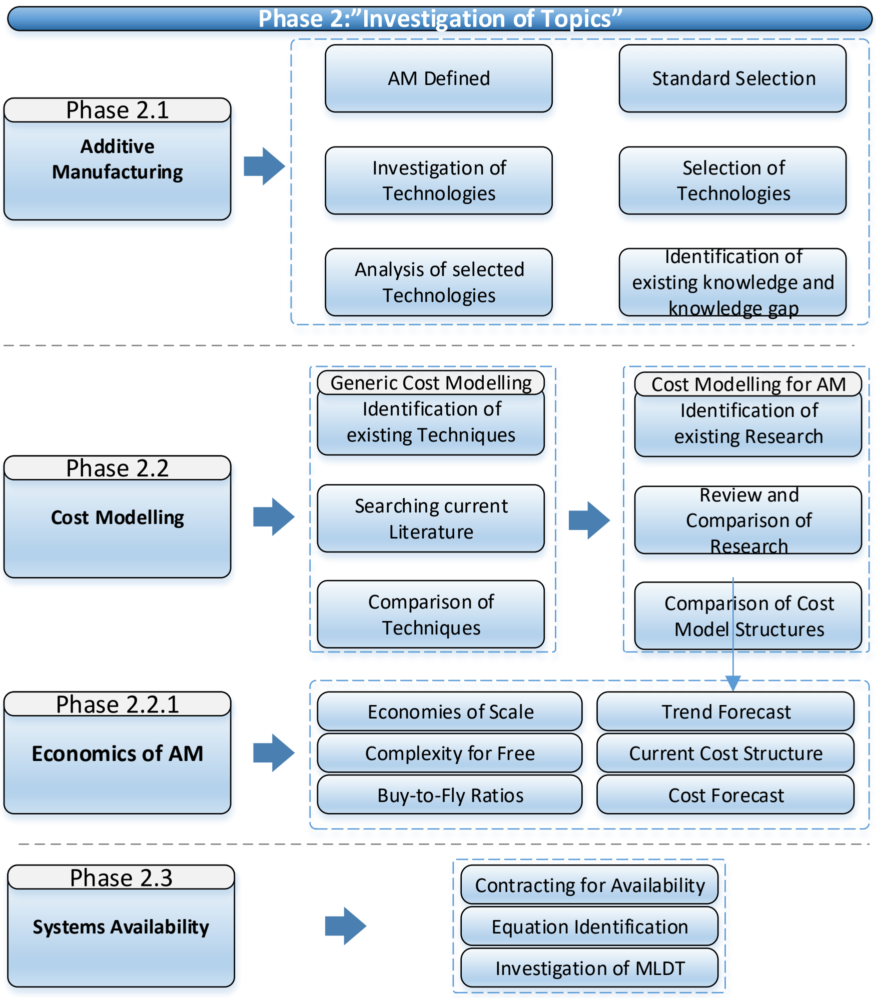


Figure 4 - Literature Review Structure

In Figure 4, it is possible to see the structure that has been followed in the Literature Review. In total, 200 journal and conference papers, 14 reports and 4 PhD Thesis have been reviewed. These sources have been selected as they cover aspects such as system analysis, cost modelling and economic aspects of AM. To assess the current research on AM, an analysis of publications has been carried out on the SCOPUS database using

“Additive Manufacturing” as keyword. A total of 2,300 publications have been published during the period between 1997 and 2017. The review is based on a lower number of publications which has been selected due to their relevance to the research scope involving, Support Services. Most publications were conference and journal paper. Figure 5 outlines the research published per year. This graph is featured by two periods. The first one between 1997 and 2009 in which publications were relatively steady, the second period between 2009 and 2014 in which Additive Manufacturing research interest has grown dramatically from 69 to 873 publications. This is mainly a consequence of a growing awareness of governments, research institutes and companies on AM benefits.

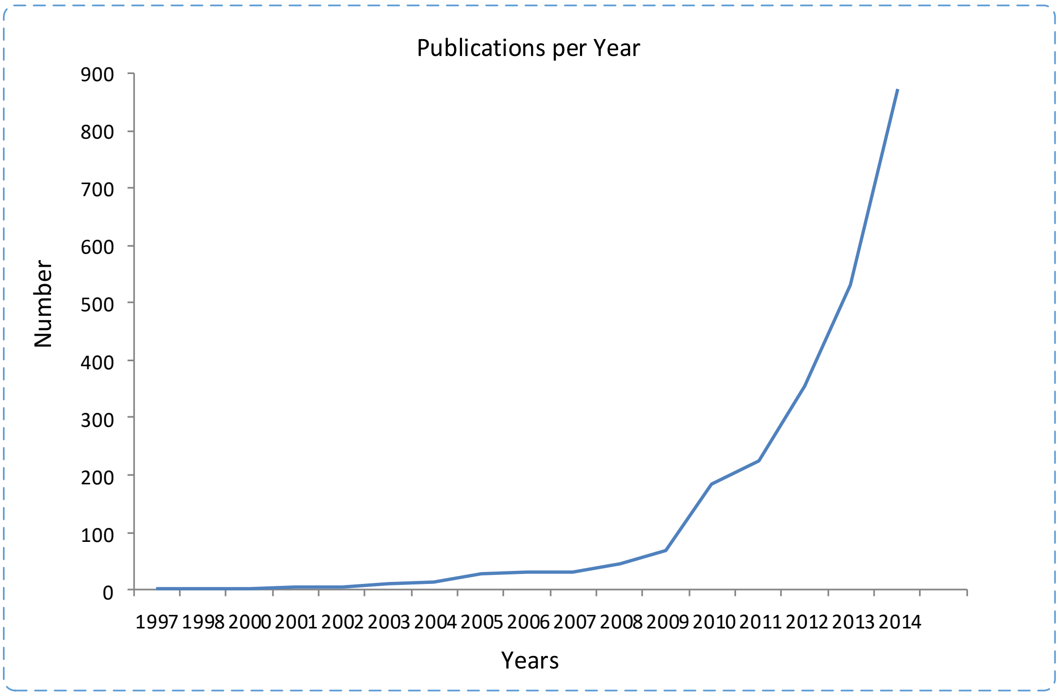


Figure 5 - AM Publication per Year

Loughborough University is leading the research with a total of 92 publications, followed by the University of Texas El Paso with 65 publications and the Katholicke Universitaet Leuven with 54. Another interesting finding is the publication by country; United States is leading with 961 publications followed by the United Kingdom with 300 and Germany with 281. If the analysis is tailored to “Cost Modelling for Additive Manufacturing” the main Institutions which have been active are: Loughborough University with 4 journal papers, Nottingham University with 1 conference paper for "Selective Laser Melting" (SLM), Cranfield University with 2 PhD theses for "Wire+Arc Additive Manufacturing" (WAAM). Another important contribution is made by the Universitat Politecnica de Catalunya which published a Neural Network model for time generation for Selective Laser Melting. Finally, the Naval Postgraduate School of California conducted research on AM implementation in US Navy platforms for supporting the systems with printing spares. Given the large number of published journals on Additive manufacturing and related cost modelling techniques, a selection of information has been carried out. Firstly, experts from the "Welding Engineering and Laser processing centre" of Cranfield have been identified and interviewed. Secondly the experts have provided the most relevant references of journals to be reviewed. Moreover, references of the journals provided have been reviewed and included.

The German research on ALM technology is dominated by Fraunhofer ILT, Fraunhofer IFAM, Technical University Hamburg-Harburg, University Duisburg-Essen and University of Paderborn:

2.2.1 Fraunhofer ILT

Considered the leading R&D center for laser technologies, the Fraunhofer Institute for laser Technology has strong links with aerospace industry and ALM manufacturers. They focus on both BDF and DED technologies.

Website: Fraunhofer ILT

Contacts: Dr. Ing. Wilhelm Meiners; Dr. Ing. Konrad Wissenbach

2.2.2 Fraunhofer IFAM

The Fraunhofer Institute for Manufacturing Technology and Advanced Materials focus on PBF technologies for metal production.

Website: Fraunhofer IFAM

Contacts: Prof. Dr. Ing. Matthias Busse

2.2.3 Technical University of Hamburg-Harburg

The University hosts the “Institutes of Laser and System Technologies” (iLAS) and the “laser Center North” (LZN) which is an application oriented institute. They own a wide variety of ALM systems. Main industrial partners: BMW, Airbus, Daimler.

Website: ILAS; LZN

Contacts: Prof. Dr. Ing. Claus Emmelmann

2.2.4 University Duisburg-Essen

The University hosts the “Rapid Technology Centre” (RTC) which focuses on Rapid Prototyping and Rapid Manufacturing. Main technology is BDF. They have a wide variety of ALM systems. Main industrial partner are: BMW, Thyssesn Krupp, Daimler, Siemens, MTU Aero Engine and various ALM manufacturers.

Website: Rapid Technology Centre

Contacts: Prof. Dr. Ing. Gerd Witt

2.2.5 University of Padeborn

The University hosts the “Direct Manufacturing Research Centre” (DMRC). The center has a wide range of PBF systems. Main industrial partners are Boeing, Siemens and ALM manufacturers.

Website: DMRC

Contacts: Prof. Dr. Ing. Hans Joachim Schmid

2.2.6 United Kingdom

In United Kingdom the ALM research is led by Cranfield University, University of Sheffield and Loghbororugh University.

2.2.7 Cranfield University

The University hosts the "Welding Engineering and laser Processing Centre" which has developed the WAAM process. Focus of research is around WAAM processes. The center owns a wide range of WAAM systems.

Website: Welding Engineering

Contacts: Dr. Paul Colegrove

2.2.8 University of Sheffield

The University hosts the "Advanced Additive Manufacturing" (AdAM) institute which is made of various centers. The centers are funded by EPSRC, ERDF and EOARD. The institutes own wide range of ALM systems and are worth mentioning that they also focus on DED. Industrial partners are BAE Systems, EADS, Xaar and Unilever.

Website: AdAM

Contacts: Prof. Neil Hopkinson

2.2.9 Loughborough University

The University hosts the "Additive Manufacturing Research Group" (AMRG) which is considered one of the leading centers for ALM research and development. Main Industrial partners: EOS, BMW and Honda.

Website: AMRG

Contacts: Prof. Russell Harris

2.3 Additive Manufacturing

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). As outlined by Campbell and Ivanova (2013), AM technology is a relatively simple process compared to traditional manufacturing which is labour intensive, requires more resources and complex processes such as machining, forging and moulding.

As outlined in Figure 6 the inputs of AM are raw materials, supports and utilities. On the control side, there is a CAD file which contains the geometry of the object and the parameters which can get up to 150 different variables. Parameters play a crucial role in the process as they have a strong incidence on object quality. On the mechanism side, there is the substrate which is the plate on which the object will be grown. The substrate is usually made of the same material which will be deposited and is recyclable. The *"American Society of Testing and Materials"* (ASTM), issued in 2013 a standard for AM technologies. The aim of the standard is to group together current AM process methodologies.

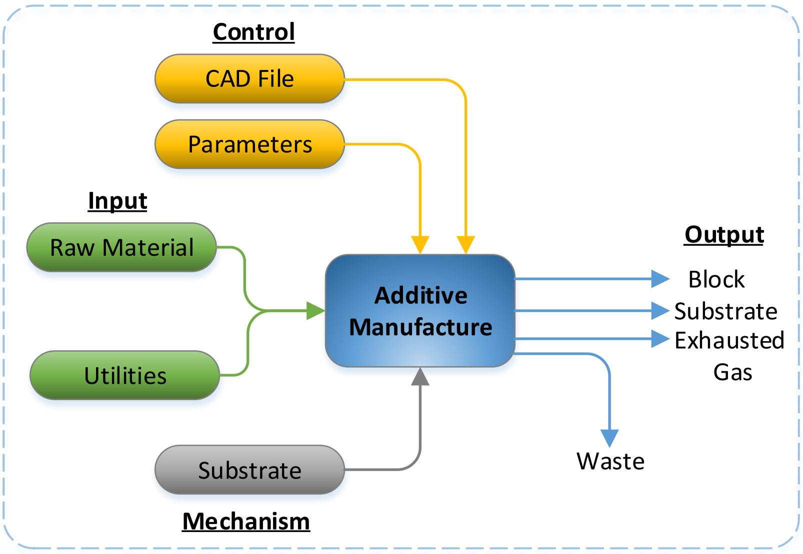


Figure 6 - IDEF0 representation of AM

The result is a group of 7 different processes which absorb all different commercial variants of the technologies. The standard definitions according to ASTM, (2013) are:

- **Direct energy deposition**: “process in which focused thermal energy is used to fuse materials by melting as they are being deposited”.
- **Powder bed fusion:** “process in which thermal energy selectively fuses regions of a powder bed”.
- **Binder jetting:** “process in which a liquid bonding agent is selectively deposited to join powder materials”.
- **Material extrusion: “**process in which material is selectively dispensed through a nozzle or orifice”.
- **Material jetting: “**process in which droplets of build material are selectively deposited”.
- **Sheet lamination: “**process in which sheets of material are bonded to form an object”.
- **Vat photopolymer: “**process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization”

Another important classification of AM is the one made by Martina, Colegrove, Williams, & Meyer (2015) which categorise the process methodologies based on energy source and feedstock type and outlines various possible configurations. Martina (2014) focuses on promising process methodologies for industrial applications therefore he does not include jetting, extrusion and lamination. Energy sources are arc and beam which are delivered through electrons or lasers. Feedstock can be wire or powder, on bed or blown. Moreover, he categorised the “Wire+Arc Additive Manufacturing” (WAAM), which is the research focus of Cranfield University. AM can be configured in various process methodologies based on components of the machine, feed type and energy source applied. Generally there are two main categories that differentiate the type of feed “Powder Bed Fusion” (PBF) and “Direct Energy Deposition” (DED) which are mainly based on wire feed Martina et al., (2015).

2.3.1 Direct Energy Deposition (DED)

Direct Energy Deposition has different energy sources. It can employ laser beam, electron beam, or plasma variants such as TIG, MIG or plasma torches.

2.3.1.1 “Wire+Arc Additive Manufacturing” (WAAM)

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. As defined by Wang et al., (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 which 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 can 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. 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.

Figure 7 - WAAM System

Per Martina et al. (2012) “Wire+Arc Additive Manufacturing” (WAAM) is a novel “Additive Manufacturing” (AM) technology which provides significant strategic advantages. The technology combines arc welding with wire feeding and can benefit from design freedom, buy-to-fly ratios as low as 1.2, potentially no constraints in size, and low cycle times. These aspects make WAAM particularly suitable for custom made, large functional components made of high value materials Ding, (2012). As described by Ding et al., (2011) WAAM consists in building 3D metallic components, by depositing weld beads one above the other in a layer by layer fashion. The result is a straight metallic wall with a minimum width of 1-2 mm, including the “waviness”. This is the material which must be removed in post-processing to eliminate surface irregularities, defined as the difference between the Total wall width and the Effective wall width (Figure 7) Martina, (2014). As outlined by Martina et al., (2012) when WAAM is compared with traditional subtractive manufacturing the reduction of waste decreases dramatically from a typical 90% to 10%. WAAM technology has various benefits over other AM technologies and traditional manufacturing. It allows near net shape or net shape manufacturing enabling strong savings in high value materials such as titanium. The deposition rates of titanium reach up to 1 kg/h, which is considerably higher than the 0.2 kg/h achieved with powder bed technologies.

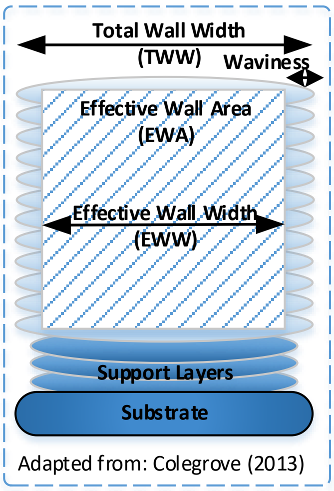


Figure 8 - WAAM Wall

The manufacturing system is fairly simple and compact, therefore suitable for applications where space is limited such as ships. The equipment required is readily available on the market and requires a low investment (circa £200k) Williams et al., (2015). WAAM Systems can be configured in different ways; different heat sources such as “Tungsten Inert Gas” (TIG), “Metal Inert Gas” (MIG) and Plasma torches are employed for different materials. WAAM configuration for Ti-6Al-4V depositions is based on plasma and requires a tent for shielding the deposition. Configuration for Stainless Steel and Aluminum do not require a tent providing the benefit of unlimited build volume, and the elimination of the set-up activities for the tent and the waiting time for purging it.

WAAM systems are made of a torch to deliver the heat input and deposit the wire, a robot or CNC to follow the paths of the geometry, a control board to control the robot, a wire feeder to control the deposition of the material and a roller which is applied between layers to improve the microstructural properties.

The purpose of this chapter is to investigate and define exhaustively a WAAM based manufacturing system. This research starts by investigating WAAM process and system aspects, outlining key information on the technology and defining all the necessary elements of the system which are necessary to accomplish its aim. Then, the operating environment within a platform is investigated. This will be used to define which key requirements need to be considered when designing the system for In-Platform applications.

Due to high heat input, components deposited through WAAM are affected by:

- Residual stress: which reduces mechanical performance of the component
- Distortion: which leads to difficulties in achieving the required tolerances

To improve these aspects, extensive experimental research has been carried out by Colegrove et al., (2013). The result is a set of mitigation strategies, which can be categorised as pre-process, online process and post-process strategies. According to Ding et al., (2011) pre-process strategies are optimisation of the parameters, clamping and optimisation of building strategy. While clamping and building strategies have a strong impact on the reduction of distortion, the optimisation of parameters affects it only slightly. Online strategies refer to the ones that occur during the deposition process and are the most effective. Balanced building refers to depositing same geometry on one side of the substrate and the opposite side. Balanced building has a strong impact on the reduction of distortion but has no effect on residual stress. Optimisation of cooling time refers to the limitation of time in order to use the existing heat to pre-heat the following layer achieving a reduction of residual stress Ding, (2012). Drawback is excessive heating of the piece; therefore, optimisation of cooling time has to be carried out. Moreover, to improve the cycle time of the deposition, parallel deposition may be carried out with a reduction of waiting time Martina, (2014).

The most promising process with strong impact on microstructure is online rolling.

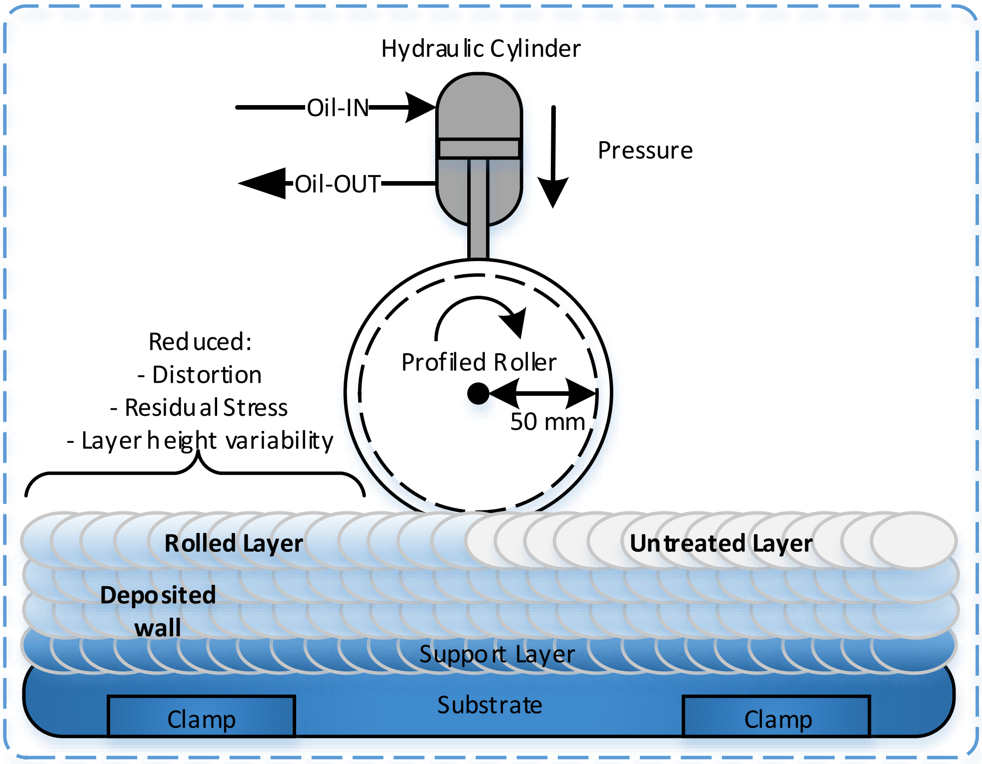


Figure 9 - WAAM Online Rolling

As it is outlined in Figure - 9, online rolling occurs after the deposition of a layer and consists in applying pressure to the wall through a hydraulic cylinder which pushes a roller. Colegrove et al., (2013) and Martina, (2014) outlined various benefits such as strong impact on microstructural refinement and improvements on residual stress.

- Reduction from 600 MPa to 250 MPa of residual stress

- Reduced layer height variability and lateral deformation (waviness)
- Improved microstructure properties, through refinement of grain size.

Conclusions of their studies indicate that rolling has impact on residual stress reduction, improved fatigue crack growth rate, improved mechanical properties such as tensile strength by 19% and yield strength by 26% QIU, (2014), Martina, (2014). Post processing strategies refer to traditional heat treatments and post-deposition rolling which has the major disadvantage of allowing only rolling on the last layer.

A detailed Quality Assurance (QA) procedure is missing in international standards such as “American Society of Mechanical Engineers” (ASME). According to Martina, (2014) current “Quality Assurance” (QA) tests on WAAM are neutron diffraction and contour method to measure residual stress and X-ray and ultrasound for defects.

Unlike from powder based processes, in WAAM the wire is entirely molten at the point of deposition and the occurrence of defects is unlikely. Appropriate selection of process parameters is not based upon modelling results, rather by relying on experimentally gathered knowledge through build and characterisation of WAAM samples.

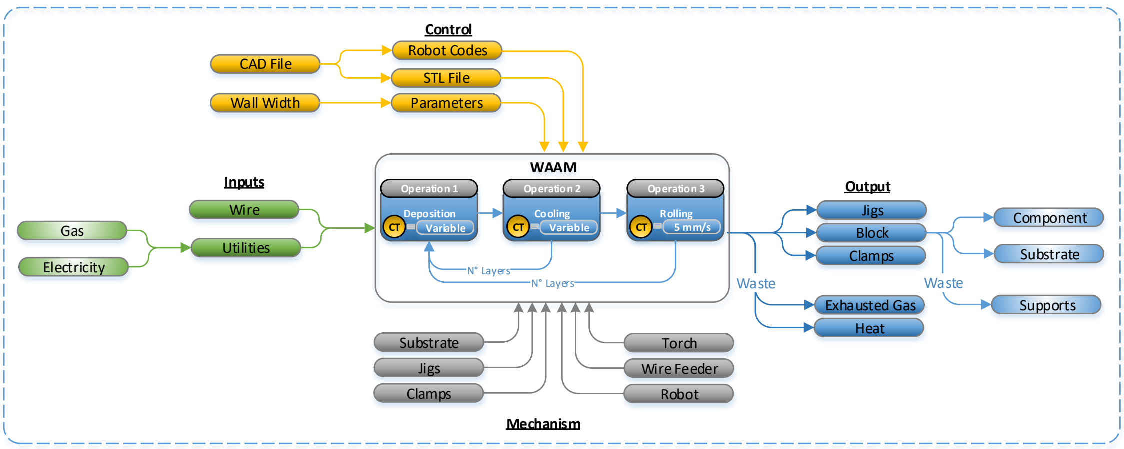


Figure 10 - WAAM IDEF0

The model outlines an “Integration Definition of Function Modelling” (IDEF0) of WAAM which has been developed to gather a deeper understanding on what are the operations, inputs, outputs, controls and mechanism of the system. To develop the IDEF0, an interview has been carried out with a researcher of the “Welding Engineering and Laser Processing Centre” of Cranfield University. The aim of the IDEF0 is firstly to provide a basic understanding on WAAM and secondly to provide the reader the logic to investigate further the deposition process, what it involves and which resources are consumed.

The inputs of WAAM 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 rolling phase to ensure microstructural refinement. In order to calculate duration of WAAM’s cycle time, Zhai, (2012) and Guo, Latham, & Xiang, (2015) developed equations to perform estimations. The following equation is employed to outline the time of the deposition phase:

$$t_w = \frac{V_{dm}}{\frac{(\pi * D^2 * WFS)}{4} * E_p} \qquad 1)$$

t_w	Time of welding
V_{dm}	Volume of deposition
D^2	Diameter of wire
WFS	Wire Feed Speed
ρ_m	Density of material
E_p	Part built efficiency

This equation is employed to outline the time of the cooling phase Grong, (1994):

$$t_c = \frac{\left(\frac{Q}{(H_m - H_{O}) * v * b}\right) * 2}{4 * a * \left(erf^{-1} * \left(\frac{T - T_0}{T_m - T_o}\right)\right) * 2} \qquad 2)$$

t_c	Time of cooling
Q	Power input to weld
$H_m - H_o$	Enthalpy to heat
T_m	Melting temperature
a	Thermal diffusivity
v	Travel speed
erf^{-1}	Error Function
T_m	Melting temperature

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. Moreover, jigs and substrate are in a trade-off situation and they are part of the building strategy phase. Their design is a critical decision and some rules need to be established to engineer these mechanisms.

Outputs of WAAM are represented by a block made of the deposited component, the supports which are deposited on the substrate and finally the substrate itself. This aspect outlines that a subsequent manufacturing process is essential to divide component from substrate. Finally, the waste of the WAAM system is the support which can be recyclable, exhausted gas which is recyclable and heat. As depositions, may last for long hours, gas consumption may become high, therefore it is recommended to consider ways to collect and recycle argon to improve the autonomy of the system.

The control side is featured by the 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, output, current, torch angle and trim. Controls are the most important and complex part of the WAAM system. To support the decision making on controls, various models, optimization studies, algorithm and support software have been developed in the “Welding Engineering and Laser Processing Centre” of Cranfield. Moreover Ding, (2012) automated the file processing activities through the development of “RUAMROB” a software with a GUI that performs automatically most of the files conversions.

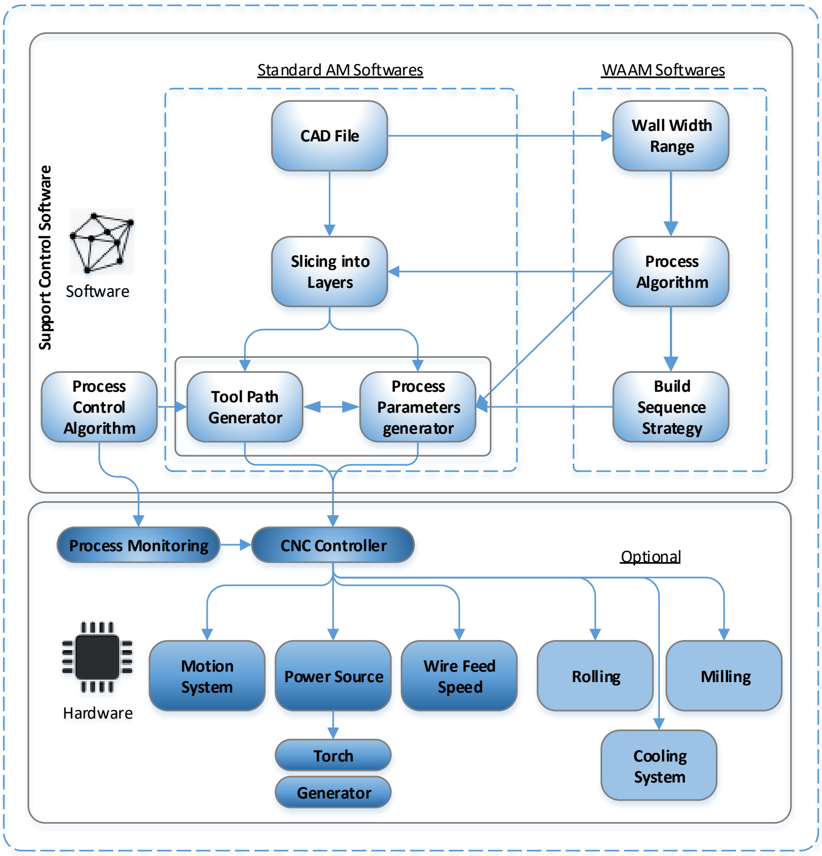


Figure 11 - WAAM System Architecture

Figure – 11 outlines the System Architecture of WAAM which is made by a software module and a hardware module Ding, (2012). The software module is divided in standard software commercially available and custom made software to support the WAAM process. This software is numerous and need to interact with each other to deliver the files to control the CNC controller which guides the WAAM process: wire feed, torch and robot. The combination of these modules interacting between each other allows the WAAM system to be fully automated and autonomous without the need of supervision and may continuously deposit without interruption. Currently research focus is on process control algorithm and online monitoring processes to govern the deposition and improve WAAM robustness and repeatability. Process monitoring may lead the WAAM system to higher reliability and ability to reproduce constantly high quality products. This is supported by Almeida, (2012) which outlines that *"the development of accurate process control models capable of determining the weld bead geometry and plate fusion characteristics from the welding process parameters is one of the crucial software components for WAAM technological and commercial development".*

Data processing activities allows conversion CAD file containing the geometry, process parameters and building strategy into a readable robot program which controls the WAAM system. Figure 12 outlines the process map of a complete data processing activity for WAAM.

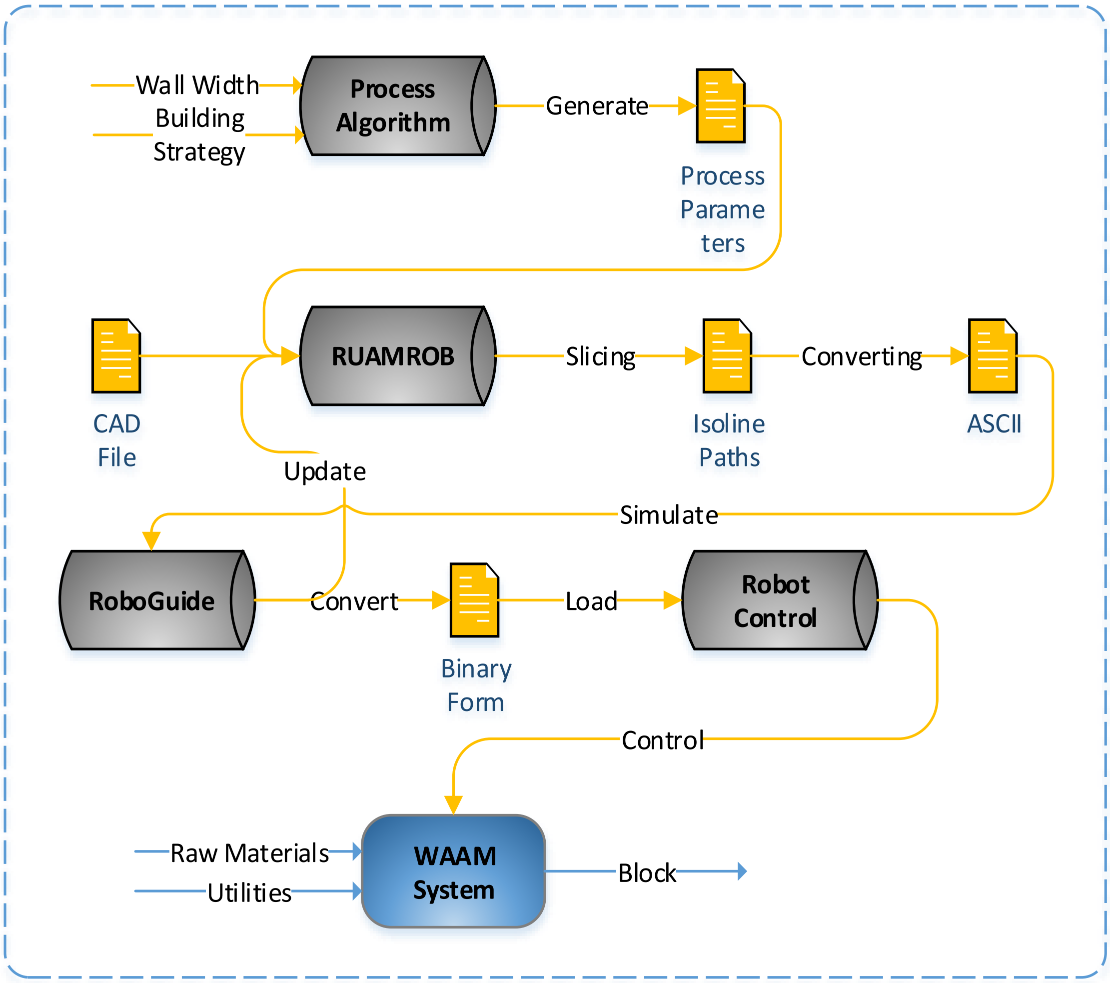


Figure 12 - Data Processing Activities

The first phase of the software is slicing the CAD file into Isoline paths which needs to be converted into ASCII format to be processed by the Robot Control. Concurrently a Process Algorithm generates a process parameters file which is developed based on wall width and building strategy information. This algorithm has been optimized to identify correct process parameters to avoid three main defects shown in Figure 13.

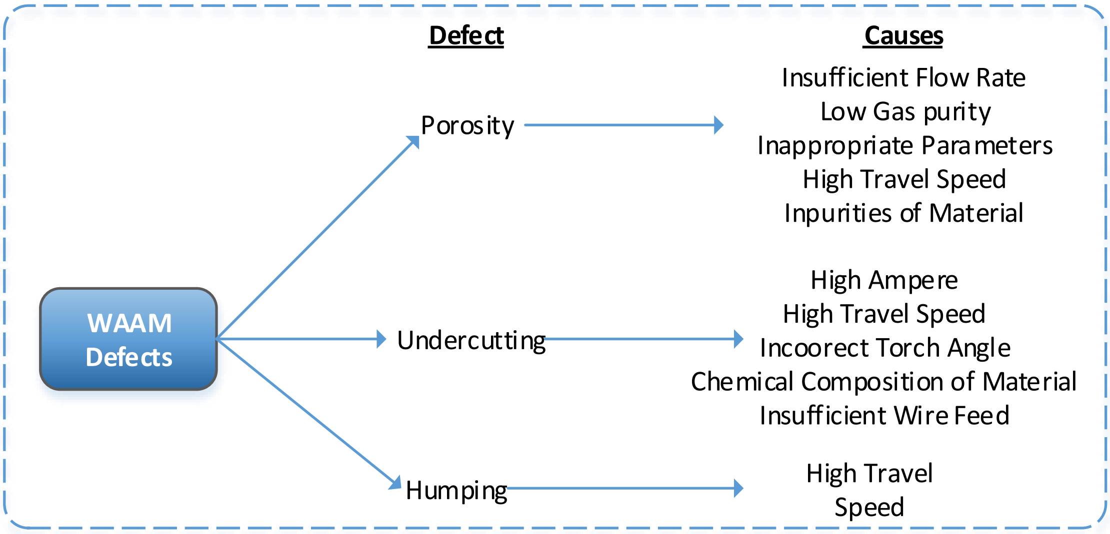


Figure 13 - WAAM Defects

Porosity refers to cavities within the weld bead and is considered a defect as it affects the performance of the weld. Undercutting refers to concavity of the weld bead which compromises the tolerances requirements. Humping refers to an uneven material deposition.

The aim of the Process Algorithm is to maximize the deposition rate to reduce as possible the building time. As explained by Martina et al., (2012) “wire feed speed, to which the deposition rate depends on, should be maximized to build the walls as fast as possible, whenever productivity is a key factor”. Therefore, the rules of the algorithm are to maximize travel speed, wire feed speed. Process model optimization charts have been developed by Adebayo, (2014) to outline and examine the interactions of wall width, wire feed speed/travel speed ratio and wire feed speed and set rules for process parameters to respect quality aspects. In the following phase the ASCII file will be tested within RoboGuide, a robot simulation software. This allows testing the robot path, updating it to avoid collisions and correct errors. As the robot program is tested in early phase it allows the elimination of waste during the actual deposition.

To outline all the necessary activities required to perform a deposition, a process map outlined in Figure 14 has been developed with the experts of the “Laser Engineering and Welding Processing Centre” of Cranfield University.

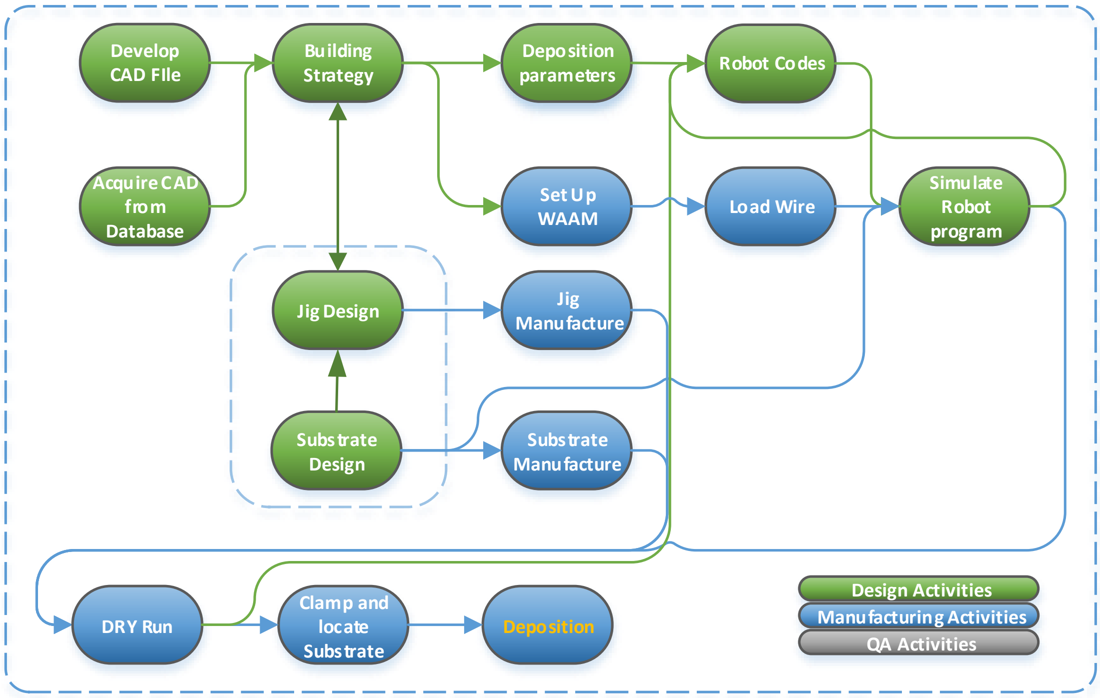


Figure 14 - WAAM Process Map

The process map outlines the sequence and concurrency of activities. These have been divided into design activities performed by design engineers, manufacturing activities performed by technician and finally quality assurance activity performed by a quality inspector.

The process starts with the development of the geometry of the component to be printed. This might be already available and stored in a database. Afterwards the geometry is analyzed and the building strategy is developed. Concurrently the jigs and substrate design is performed. These are part of the building strategy and in trade-off, therefore increasing substrate size result in a reduction in jigs size.

The following phase consists in developing the deposition parameters perform setup activities, which generally takes up to 1.5 hour and manufacture jigs and substrate. Substrate manufacturing is a standardized process as is based on cutting and de-burring standard metal sheets with different thickness. Jigs manufactures require a high level of customization and therefore needs to be manufactured tailor made. Lead times of both activities are difficult to estimate as they are not standard. To guide the robot to perform the designed path, a robot code needs to be generated and in parallel the wire needs to be loaded on the machine. Afterwards the robot code should be simulated with the design of the substrate to check if conflicts occur. Moreover, a dry run with actual substrate and jigs is considered necessary to perform a second check for conflicts. During the deposition, conflicts might compromise the entire build, the substrate and damages to the torch may occur.

Once the dry run has been performed and the process has been cleared the deposition can start. The deposition process is featured by various operations. This depends on the WAAM System configurations. As reported in Figure 11 the classic configuration is made by three operations: deposition, cooling through waiting and rolling. Integrated WAAM allows a strong reduction in setup time as this occurs just once and milling after deposition allows improving dramatically the accuracy of the wall and reducing also the waviness. After the deposition, a cooling phase is required to cool down the component to avoid damages to instruments for measurement. This phase may take some minutes depending on the volume of the part and the cooling times adopted during the deposition process.

Figure 15 outlines a process map of a complete WAAM System; it outlines the sequence of processes and the minimum number of equipment to convert geometry into a functional component. Moreover, the process map outlines the flow of the product and the inputs of equipment such as electricity, gas, compressed air and cooling solutions. The outputs have been divided in critical and non-critical. Critical outputs might be noises and vibrations while non-critical are waste such as the waviness which is removed from the component and the heat which occurs during each process. Another important aspect is the revitalization loop for the substrate, which consists in removing the supports.

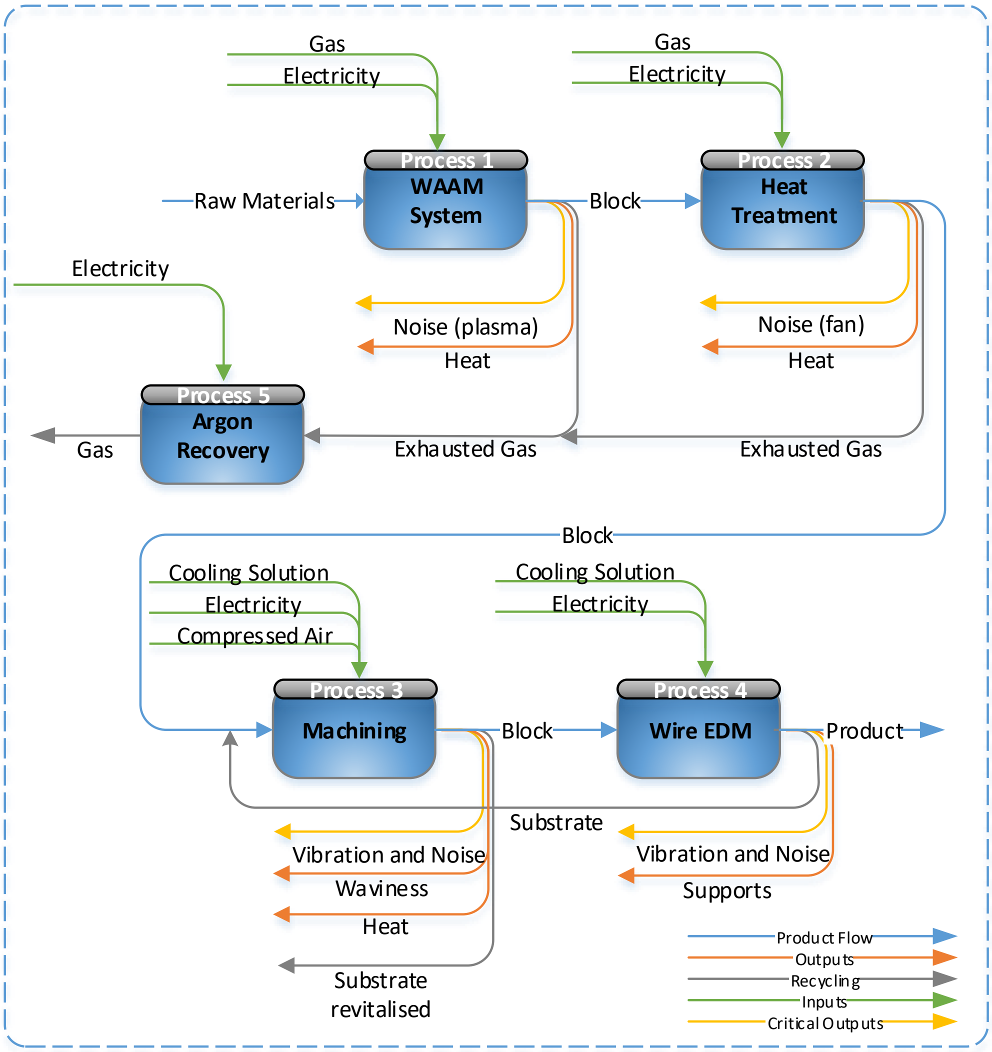


Figure 15 - WAAM Manufacturing System

To reduce the stocks of gas and prolong the autonomy of the system, plasma torch with localized shielding should be employed to eliminate the need for tent purging. Moreover, argon recovery equipment has been included. This is due to high consumption of argon during the whole deposition process which may take more days and the heat treatment which needs to be performed in inert atmosphere to avoid oxidation of the material. Moreover, a fixed gas distribution system should be included to minimize gas cylinder handling which is time consuming and requires lifting equipment. To reduce vibration in input and output and to compensate potential blasts and reduce noise levels on the WAAM System, equipment needs to be installed on anti-vibrating bushings. Aspects such as potential load, stiffness of structures, working life, operating temperature and weight need to be considered to perform the design of the bushings which consists in an elastomer study, selection of materials and technology. Aspects such as potential load, stiffness of structures, working life, operating temperature and weight need to be considered to perform the design of the bushings. Platforms which operate in sea may be subject to oscillation due to waves. This aspect may influence negatively the WAAM deposition as the weld bead core is partially in a liquid state which may lead to increased waviness. Nevertheless, this aspect is limited in WAAM as it is a wire fed process. Technologies based on powder beds require a high accuracy in powder spreading over the substrate.

2.4 Cost Modelling Techniques

Product Cost estimation play a significant role in the evaluation of AM. It represents the basis to develop the key decision variable on AM, which is the cost of product. Cost estimation is directly linked to business performance. The following section aims at presenting the review on cost modelling techniques and cost types.

Non-recurring Costs are defined this way because they occur only once in the lifecycle of the work activity. These are capital expenditures that incur prior to the first unit of product is produced and they incorporate also all the efforts required to develop and qualify the product and process. Typical examples are: 1) initial engineering effort, 2) test of equipment, 3) jigs and tooling acquisition/upgrade, 4) planning and 5) engineering models (Curran et al., 2004).

Recurring Costs are ongoing costs that are proportionally incurred from the production of the first unit of output of the manufacturing process. These are required in order to maintain and update the manufacturing setup. An important feature of the recurring cost is that potentially they decrease during time as they are linked with the learning and improvement curves. Typical examples are: 1) commercial procurement, 2) production overheads, 3) material procurement and 4) consumables (Curran et al., 2004).

Fixed Costs are defined as the cost of manufacturing which do not varies when the output rate of production is altered. These costs are independent and not linked with the enterprise performance and they incur to keep the enterprise operational. Typical examples are: 1) building and facilities, 2) insurance, 3) salaries of permanent employees and 4) equipment.

Variable Costs are costs of production which varies according to the output rate. Typical examples are labour, material costs and machining (Curran et al., 2004).

Fixed and Variable costs can be further broken down into direct and indirect costs. Direct costs are those that can be easily associated to its cause and usually are associated to the bill of material. Indirect costs are those that cannot be easily attributed to a cause. For example some indirect costs are: 1) electrical power, 2) cleaning of the facility and 4) building works/maintenance.

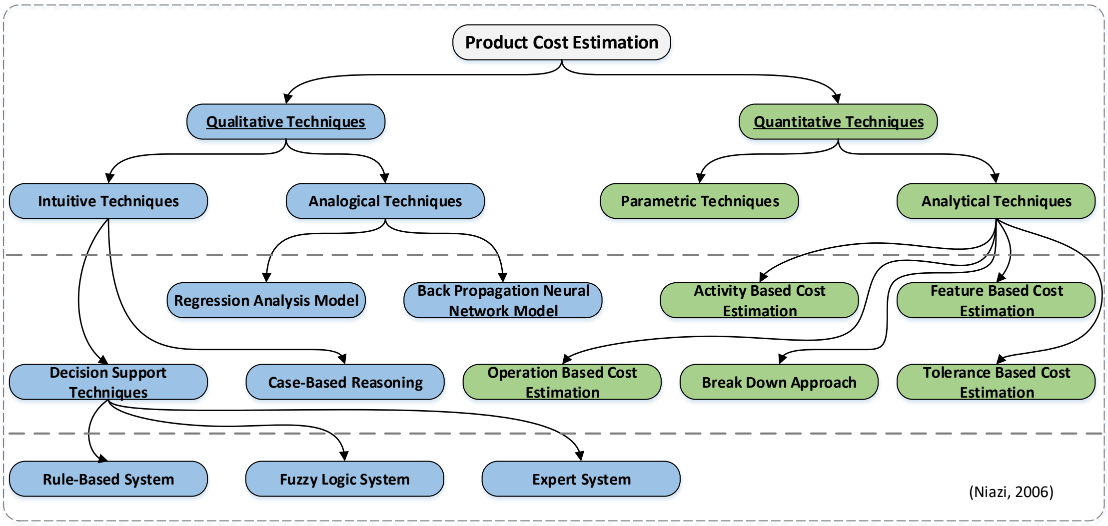


Figure 16 - Cost Estimation techniques

Overpricing may result in a loss of sale while under-pricing may lead to a financial loss. Niazi, et al., (2006) performed a detailed review of the state of the art in Product Cost Estimation covering exhaustively the various techniques available today. The following sub heading will cover “Intuitive Techniques”, “Analogical Techniques” and “Analytical Techniques”.

2.4.1 Intuitive Techniques

Case Based Reasoning technique adapts past design information collected from a database to the new design. It uses past experience to synthesise the new design Niazi et al., (2006). Ideally the old and new design should have strong similarities. Often this does not occur and changes to parts and assemblies need to be carried out. Missing information and data must be collected and implemented. This process of improving the design is carried out until the design conforms to the specifications. Ahn et al., (2014) suggests that to increase the estimate accuracy, it is necessary to prioritise the attribute impact within the model. This is supported by Kim and Kang, (2007) who demonstrated that by eliciting domain knowledge from experts and performing weight of attributes will result in a more accurate and reliable estimate. This approach is particularly suitable in early stages design such as the conceptual stage. Decision Support techniques are particularly suitable for evaluating design alternatives and they are developed to assist the estimator during the decision-making process. Data and information are provided by a database which stores knowledge of experts and artificial intelligence is used to orient this knowledge toward problem solving Niazi et al., (2006). There are three main categories of Decision Support Systems defined by Niazi et al., (2006): *Ruled Based System which* "are based on process time and cost calculation of feasible process from a set of available ones for the manufacture of a part based on design and/or manufacturing constraint". *Fuzzy Logic Systems:* particularly helpful in managing uncertainty and getting reliable and accurate results. They are not appropriate for complex results as they require significant effort. *Expert Systems:* are defined as "a system based on storing expert knowledge and manipulate it based on demand. The systems aim to mimic a human expert with an automated logical reasoning approach.

2.4.2 Analogy Techniques

Regression analysis techniques are based on the use of historical data to establish a relationship between the product cost of past designs and the values of certain selected variables. This relationship is used to forecast the cost of the new design. They have well defined mathematical background which makes this technique very reliable. The aim is to investigate the contribution of each variable to the overall cost. Significant variables are identified through statistical test and are combined into Cost Estimation Relationships (CERs). Major advantage of this technique is the ability to interpret the relationship between variables and costs. To achieve this, there must be a linear relationship between independent variables and costs. Moreover the variables need to be independent from each other Verlinden et al., (2008).

Table 1 - Technique Comparison

Technique	Advantages	Disadvantages
Intuitive	-Quick to produce and flexible -Few resources in terms of time and costs -Can be accurate as other more expensive methods -Can provide optimised results -Handles uncertainties -Quicker, more consistent and reliable result	-Prone to bias and error -Inconsistent and unstructured process -Nondeterministic as each expert reaches different estimates -Dependent on part designs -Time consuming -Might require complex programming skills
References reviewed: (Rehman & Guenov, 1998) (Shehab & Abdalla, 2002) (Gayretli & Abdalla, 1999) (Shehab & Abdalla, 2001)		
Analogy	-Reasonably quick and based on actual data -Few data required -User knows the origin of the estimate -No requirement of full understanding of problem -Accurate -Simple method and deals with uncertain and non-linear problems	-Subjective adjustment -Accuracy depends on similarity of items -Difficult to assess effect of design change -Blind to cost drivers -More difficult than parametric method -Does not handle innovative solutions -Completely dependent on data
References reviewed: (Pahl, Wallace, Blessing, & Pahl, 2007) (Cavalieri, Maccarrone, & Pinto, 2004) (Man-Yi Chen & Ding-Fang Chen, 2002)		
Analytical	-More accurate than analogy and parametric methods -Detailed breakdown useful for negotiation -Suitable when all characteristics of product and production process are well defined -Alternative process plans can be evaluated to get optimised results Easy and effective method using unit activity costs	-Slow execution -Detailed data may not be available -Inappropriate for estimation at design stage -Detailed cost information required about resource consumed -Requires detailed design information -Requires lead times in early design stage -Time consuming requires detailed design and process planning data

References reviewed: (Niazi, Dai, Balabani, & Seneviratne, n.d.) (Kiritsis, Neuendorf, & Xirouchakis, 1999) (Son, 1991) (Bernet, Wakeman, Bourban, & Månson, 2002) (Singh, 2002) (Sfantsikopoulos, Diplaris, & Papazoglou, 1995)

Back Propagation Neural Networks or Artificial Neural Networks (ANN) is an Artificial Intelligence approach which can be applied to investigate the Multi- and Non-Linear-relationships of elements. These techniques are suitable for cost estimation problems in the early stage of a design process. The accuracy of the estimates can achieve good accuracy levels even when adequate information and data are not available Niazi et al., (2006). The main advantage of ANN is that they do not require production process and product characteristics to be well defined. They are considered the last generation of tools for Product Cost Estimation and they are based on imitating the behaviour of experts when determining the main variables that rules the cost estimation Duran et al., (2012). One of the key features of ANN is that they are able to identify the relationships between product features and costs. Vouk et al., (2011) explains that ANN works on the principle of establishing a relationship between input and output which is defined as a set of rules. The developer must train the ANN which will learn these relationships and based on this when inputs are changed, the ANN can predict the outputs.

Parametric models express cost as a function of its constituent variables Niazi et al., (2006). Cavalieri et al., (2004) explains that these variables are usually associated with the cost drivers, which are features of the product such as its performance, morphology and material. The cost estimating relationships (CERs) are the mathematical form which comprise all the variables/cost drivers and are expressed as a function. To develop the CERs, the parameters of the product which best explain its associated cost need to be identified. Secondly the historical data of this cost must be normalized as companies are changing, learning and improving and currency value is constant.

2.4.3 Analytical Techniques

Feature Based Costing aims to identify the feature of the products which are associated with cost. Usually these features are related or with the design, such as the design complexity or with the related processes needed to achieve certain standards of quality

Niazi et al., (2006). Little work has been carried out on Feature Based Costing due to its low flexibility.

Operation Based Costing requires a wide range of data and information. They are not suitable for early design stage but perform well in the final stages when most of the information is available. The logic behind this method is identifying all the activities involved in the manufacturing process and outline a time for each activity. They also take into consideration setup times and non-productive times Niazi et al., (2006).

Tolerance Based Costing is based on estimating the cost by considering the design tolerances of the product as a function of the product cost. Usually the estimation process is carried out with three models: 1) unit cost of production model, 2) quality model and finally 3) lead-time model. The aim is to obtain the best tolerances and outline a range of suitable design variables.

Activity Based Costing (ABC) calculates the cost occurred in performing a manufacturing operation. This approach provides the ability to proportionally distribute the overheads over the activities involved in the production of the product Niazi et al., (2006). According to Carli & Canavari, (2013) the methodology has been developed to face the increasing level of fixed costs in modern companies. ABC "measures costs and performances of activities, resources and cost objects, assigns resources to activities and activities to cost objects based on their use" Carli & Canavari, (2013). Major contributors to cost modelling for AM are Hopkinson & Dicknes, (2003), Ruffo & Hague, (2007), Lindemann, (2012) which focused on "Powder Bed Fusion" (PBF) methodologies while Zhai, (2012) for "Wire+Arc Additive Manufacturing" (WAAM) a "Direct Energy Deposition" (DED) technology. All approaches are based on Activity Based Costing, Lindemann, (2012) outline that its major advantage is the consideration of different influence factors on the basis of the use of resources. Lindemann, (2012) model, based on ABC helped to better understand the cost structure of a product built through AM.

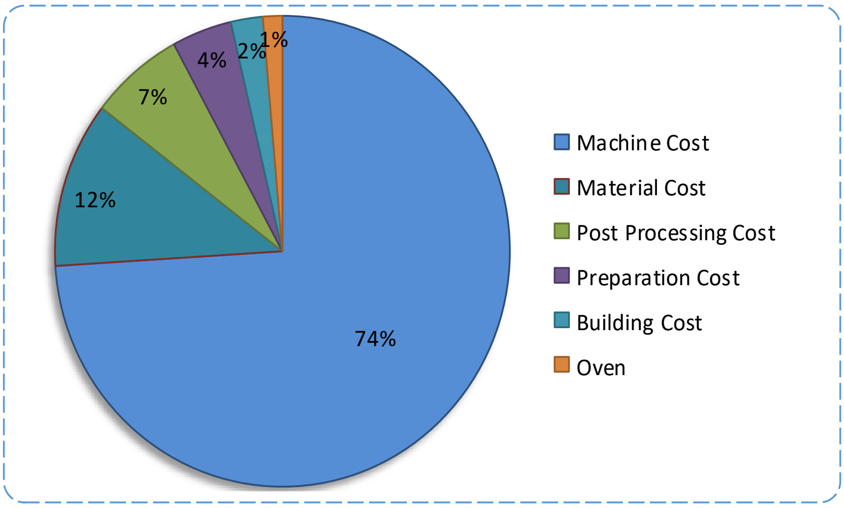


Figure 17 - AM Cost Structure, source: Lindemann (2012)

As the model is based on ABC cycle times of machines play a crucial role. Figure 19 outlines the results of a deposition of 6.3 ccm per hour. The major cost driver is the machine cost which represents 74% of the total product cost. In a second simulation based on a deposition of 20 ccm per hour, machine cost dropped to 46%. Machine cost is followed by material cost which consist of the metal powder. Currently the metal powder industry is unable to benefit from economies of scale and powder costs are relatively high. In the future metal powder demand will increase dramatically allowing producers to achieve more competitive prices Mellor et al., (2014). Remaining costs are post processing to achieve material quality required, preparation cost which refers to all the data processing activities, oven cost and building process. (Thomas & Gilbert, 2014) outlined that the hidden benefits of AM need to be investigated and outlined in order to provide an exhaustive approach to better understand AM implications.

Lindemann, (2012) and Ruffo & Hague, (2007) have broken down the deposition process into its consituent elements and they associated an occurring cost with an activity. Therefore time represents the most important variable as it will influence dramatically all the results. According to Lindemann, (2012) the deposition process is broken down into preparation, deposition, removal of product and post-processes. This structure lacks details and might not be so representative of the real world. Lindemann, (2012) emphasise that the estimation of the deposition time is the most important factor as it is the major influencer of total cost. Ruffo & Hague, (2007) divided the deposition process into its operations such as time to add a layer, time to pre-heat the layer, time of scanning, and time to cool down. The sum of these times will provide the cycle time of the machine. Zhai, (2012) estimated the product cost of the "Wire+Arc Additive manufacturing" process. Zhai, (2012) developed the model to make a comparison between the manufacturing of a component by adding material with WAAM and by removing material from a block with CNC. The application of the component is for aerospace industry which seeks to adopt lower buy-to-fly ratios due to high costs of materials and high scraps. The focus of the research was to investigate the impact of the two processes on buy-to-fly ratios. The results provided sufficient data to outline the major advantage of the WAAM process in near net shape manufacturing compared to CNC. As it is outlined in Figure 18 a deposited wall with WAAM is featured by two areas, the total wall area and the effective wall area. The difference between these two areas is the waviness which is a non-active part which will be removed with CNC. The deposition efficiency is calculated through a ratio of effective wall area over total wall area. Generally WAAM components have a deposition efficiency of 93% (Martina et al., 2012). The remaining 7% is made of previous stated waviness.

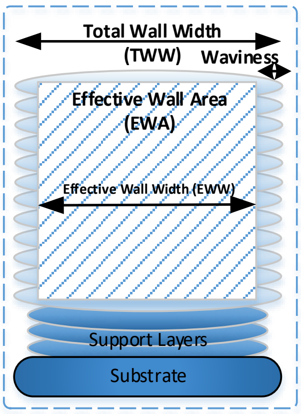


Figure 18 - WAAM Wall

The results on the cost structure were dramatically different from the results of PBF process methodologies. Due to lower capital investment and higher deposition rates (i.e. titanium 3kg/h and SS 10 kg/h) major contributor to product cost is setup cost 28%, followed by welding material 27% and welding cost 25%. An additional aspect outlined is the configuration of the machine which can be independent or integrated in which WAAM and the CNC machine are combined. The integrated configuration allows reducing dramatically the setup costs. Moreover, Zhai, (2012) outlined that by increasing wire feed speed and a related energy density, this will reduce dramatically the total cost of WAAM. The wall must rely on few layers of supports when the component and the substrate are not combined. The supports layers represent the location for the cutting and separate the substrate from the component. The following section will investigate economic aspects of Additive Manufacturing, providing the reader a deeper understanding on the financial implications of the technology.

Various authors have developed AM mathematical models. 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 cots, 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 et al., (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 could model the costs associated with the alteration of the orientation of the part within the build chamber.

Lindemann et al., (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 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 factor 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 on the buy-to-fly ratios. The cost model has been developed combing process mapping and “Activity Based Costing” (ABC). The literature review raised that “Activity Based Costing” (ABC) is the most common cost estimating technique used for costing Additive Manufacturing. This is due to its ability to provide robust estimates and spread manufacturing overheads to targeted activities. Additionally, ABC does not require a wide range of historic data and a reliable model can also be developed through interviews, observation and deduction. This technique has been adopted by Ruffo and Hague (2007), Ruffo et al. (2006), Lindemann et al., (2012), Hopkinson and Dickens (2003) and Zhai (2012). The approaches of the different authors are similar, they all break down the manufacturing process outlining all the activities involved in the deposition process and allocate a time and rate of machine, equipment and operators. Their findings are concerned with product cost and outlined that for PBF components major cost driver is the machine; this is due to slow deposition rates and high investment costs with the machine. In case of DED the major contributor to cost is materials but a comparison with a traditional subtractive process outlined that in fact there is a major cost saving due to higher material efficiency.

2.5 Economics of Additive Manufacturing

Compared to traditional manufacturing methods, AM does not benefit from economies of scale. This is due to two main constraints, slow deposition rates and limited built capacity. According to Ruffo & Hague, (2007) and Hopkinson & Dicknes, (2003) the behaviour of AM costs over units produced, benefit from an initial reduction in manufacturing costs but then the trend stabilises.

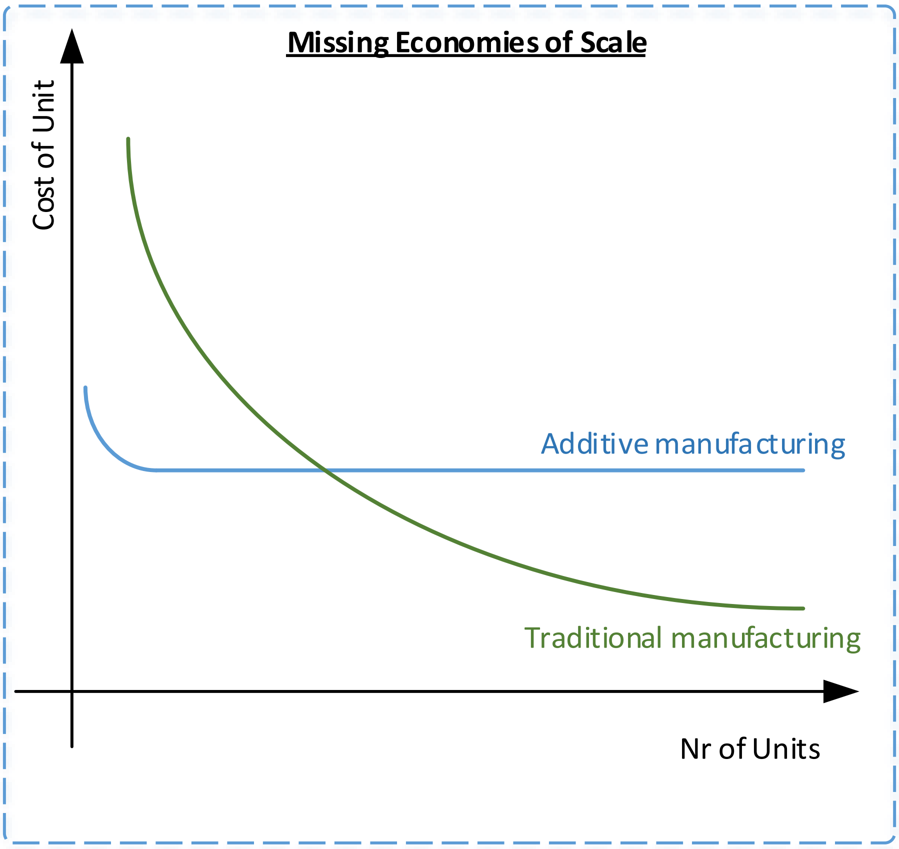


Figure 19 - AM Economies of Scale, source: Hopkinson and Dickens (2003)

According to Mellor et al., (2014) this might represent an advantage as mass production is shifting towards developing countries while EU and USA markets are focusing more on low volume and high value added productions featured with innovation, customisation and sustainability.

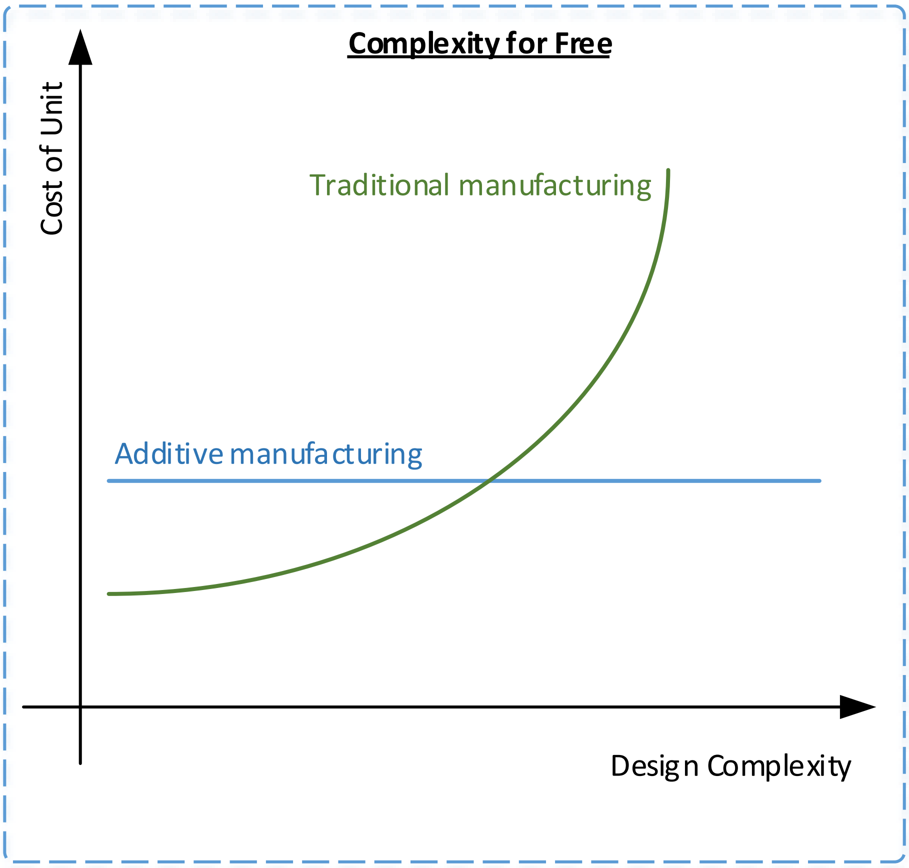


Figure 20 - AM Complexity for Free (Hopkinsons, 2003)

AM is considered a more suitable technology for economically sustainable small to medium volume productions. Moreover the technology allows design complexity for free, as outlined by Baumers, (2012) AM inputs are not correlated to design complexity suggesting that financial production cost is independent of complexity. In traditional manufacturing methods, high level of customization might result in prohibitive manufacturing costs. This is due to high investment in modifications of the manufacturing line. This suggests that AM might have a higher product cost compared to traditional methods but if positioned correctly, the technology might give strategic advantages. For example, in high value and technology advanced products. Moreover, Zhai, (2012) outlined the Buy-to-Fly ratio of the WAAM process. This index is an important measure to evaluate the suitability of a manufacturing process and it measures the material efficiency. The research showed that by reducing Buy-to-Fly ratios manufacturing cost reduces dramatically. This is mainly due to an improved near net shape deposition involving reduced material scrap. Additionally Zhai, (2012) outlines that WAAM process is particularly beneficial for Titanium depositions due to the high cost of this material. Roland Berger (2014) states that the forecast on deposition rates is promising, achieving up to 80 cm3/h by 2023, and making the technology more competitive in terms of cost and lead time.

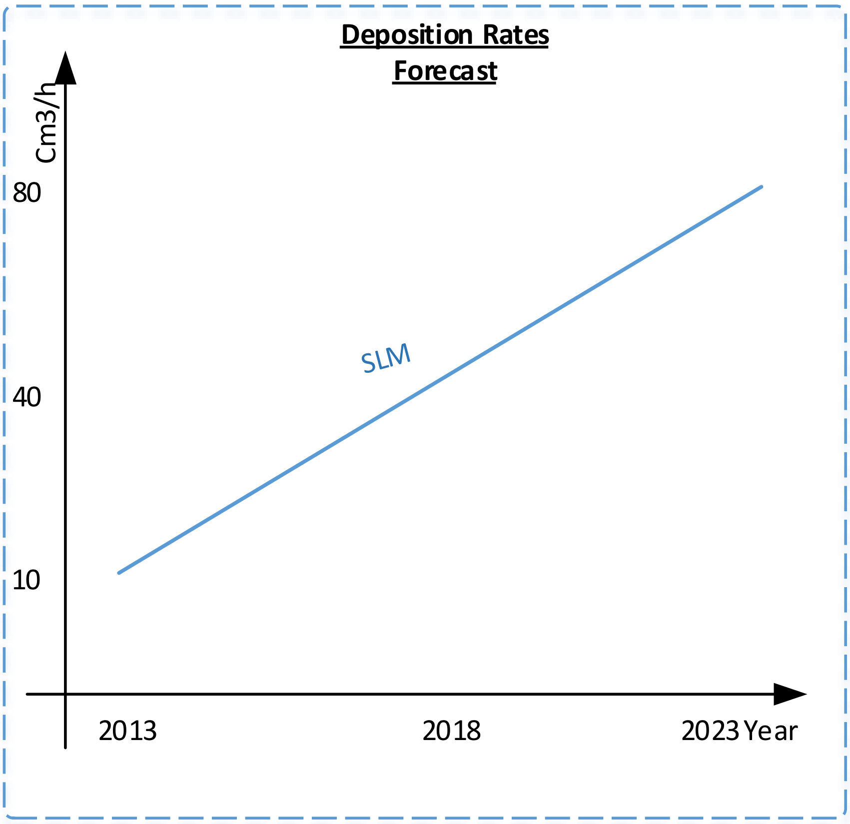


Figure 21 - Deposition Rate Forecast (Roland Berger, 2014)

Increasing deposition rates will have an impact on both, product cost and product cost structure. Lindemann et al., (2012) outlined a comparison of product cost structure with different deposition rates. By increasing deposition rate from 6.3 ccm/h to 20 ccm/h the incidence of the machine cost will drop from 75% to 48% providing a more competitive product cost. Higher deposition rates result in shorter cycle times of the machine. This implies lower human resources to be allocated to that product, providing more yearly capacity and improving responsiveness to demand. According to Berger, (2013) the current cost per cm3 is around 3.1 Euro and by 2023 it will drop to 1.1 Euro per ccm.

2.6 Additive Manufacturing applications in Defence

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 et al., (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 systems on defensive platforms. In the same year Busachi et al., (2015) 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 ALM 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 ALM 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".

2.7 Literature Review Outcome

The literature review outlined that current AM technologies available on the market are: "Direct Energy Deposition", "Powder Bed Fusion", "Binder Jetting", "Material Extrusion", "Material Jetting", "Sheet Lamination" and "Vat Photopoly". Powder based processes have higher cycle times and higher accuracy. These are employed for small to medium size components with complex geometries for enhanced functionality. Wire based processes are faster but the accuracy level drops dramatically. Wire based solutions are employed for larger components in which accuracy levels are not the most important factor.

Metals	Powder Based	Wire Based
Deposition Rate	0,2 Kg/h	3 Kg/h
Maximum size	35x30x20 cm3	Potentially no limit
Accuracy	25 micron	1-2 mm
Equipment Cost	>£300k	£200k
Material Cost	£500/kg of Powder	£150/kg of wire

Figure 22 - Technologies comparison source: (Martina, 2015)

Martina, (2014) made a comparison of these two process methodologies for titanium applications. Powder based results are from a Selective Laser Melting machine while Wire Based results are from a "Wire+Arc Additive Manufacturing" machine. As it is outlined in Figure 19 the wire based solution has various advantages compared to the powder based solution. Lower investment cost, significantly higher deposition rates, lower costs of raw materials and no limits on build size make this solution particularly promising and attractive to industry. Secondary advantages are related with the elimination of preheating phases, no vacuum required and therefore lower element vaporisation. Powder based solutions provide the user with enhanced design freedom. The accuracy level, up to 25 microns, gives the designer the possibility to access a large number of geometries. Higher accuracy level implies lower deposition rates which in some situations has a strong impact on lead times. This might represent a barrier of powder based technologies. Deposition rates are influenced by energy density, scanning speed and layer thickness. Optimisation studies based on these parameters are a focus of study of Academia and Research Institutes to make these technologies more suitable for industrial applications. Moreover, from the literature it was possible to outline product cost structure of the two different processes and results showed that in PBF methodologies, the major contributor to cost is the production rate of the machine due to high investment cost and slow deposition rates. In the case of WAAM process, the major contributor to the cost structure is material followed by the cost of deposition.

To measure costs related with AM depositions, various techniques have been investigated. According to Ruffo & Hague, (2007) traditional cost modelling techniques have various disadvantages such as the inability to provide non-financial information which are critical to decision making. Moreover, they lack accuracy providing high uncertainties in the estimate. Generally Intuitive techniques are subjective and results may vary dramatically based on experts interviewed. Furthermore, they are dependent on design features which in this case are not available. Analogical techniques are considered not fit for purpose as they depend heavily on data and in this case, historical data is not available as the system is still in the design phase. To achieve higher accuracy, wide range of information and a realistic and detail allocation of overheads, an analytical technique has been selected, "Activity Based Costing" (ABC). The literature states that this is the main technique used for cost modelling of AM. The technique assigns manufacturing overheads to activities in a more logical manner tackling the problems related with high overhead distribution. In addition, ABC, does not require historical data as the model can be developed based on process maps and interviews with experts. As outlined the main benefits of ABC is the allocation of costs according to where they are incurred improving accuracy and relevance. This allows detailing the cause of cost allowing the user to perform cost reduction analysis. To build the cost model, various documents must be developed to gather all the necessary information and data required. The most important document as reported by Zhai, (2012) is the process plan which outlines all the necessary manufacturing operations, the setup and unload activities and the post processes. This document organises the previous elements in a sequence and outlines the incurring times and resource consumptions. Another important document which needs to be developed is an IDEF0 map, as this provides details on inputs, output, controls and mechanism providing a more exhaustive approach to identify the sources of cost. To transform the data in cost, hourly rates of operators, machines and software has to be calculated. This can be done in different ways moreover the allocation of overheads may vary dramatically based on organisation type and has to be adapted on a case by case basis.

The context of support services for Defence platforms involves the selling of the availability of one or more systems. The provider’s profitability is dependent upon its ability to ensure high levels of availability over a long period (years). Traditionally this is made through the accumulation of components into warehouses within the platform. With a support service system based on AM, stocks of components can be reduced dramatically; this is due to the ability of the system to print the required component only when it is necessary. AM is particularly suitable for this application because it can process randomly any geometry without the need for adapting the manufacturing system to features of the component (no impact on setup activities). This aspect can cope with the randomness of failure rates of systems within the platform. As the components are printed in-platform, the lead time is reduced dramatically. Moreover, material efficiency and low Buy-to-Fly ratios of AM, leads to the conclusion that AM has a major advantage over subtractive manufacturing by providing better usage of materials. This aspect outlines the suitability of the technology for applications in Defence, Aerospace and Medical industry where advanced materials may reach high costs. Finally, the last part of the review outlined that the equation of availability might be improved in two different ways. An internal way is the optimisation of the reliability of the component and the reduction of time to maintain. An external way is the reduction of the delivery time which is affected by the procurement delay and the supply of the part. As AM is an enabler of delocalised and rapid manufacturing it is concluded that the technology can optimise availability of systems through the in-field production of the component on demand.

2.8 Findings

The review presented the various AM technologies which are currently under development in both industry and research institutes. Moreover, various available cost modelling techniques have been investigated. The discussion section provided a critical review of both, the technologies of AM and the cost modelling techniques allowing comparison of different approaches.

The main inferences that can be deduced from the literature review are:

- Powder bed technologies are more applicable to small complex geometries given their high accuracy levels.
- Blown powder technologies are highly suitable for repairs but also suitable for medium to low complex geometries.
- Wires fed technologies are highly suitable for large functional components given their high deposition rates.
- Activity based costing seems to be the most used technique to perform product cost estimation of AM products.
- There is no evidence on research of complete AM production systems which include also post processes.

To gain exhaustive understanding of AM based production systems, research institutes and industry should design an AM based system complete with all the necessary post processes and outline all the workers required and the activity involved in the whole production system to have a final product. This will allow to perform an actual, reliable cost estimation of additive manufacturing products.

3 Research Methodology

This chapter describes the methodology followed to carry out this PhD. The methodology is made of seven phases in total and is outlined in Figure - 23.

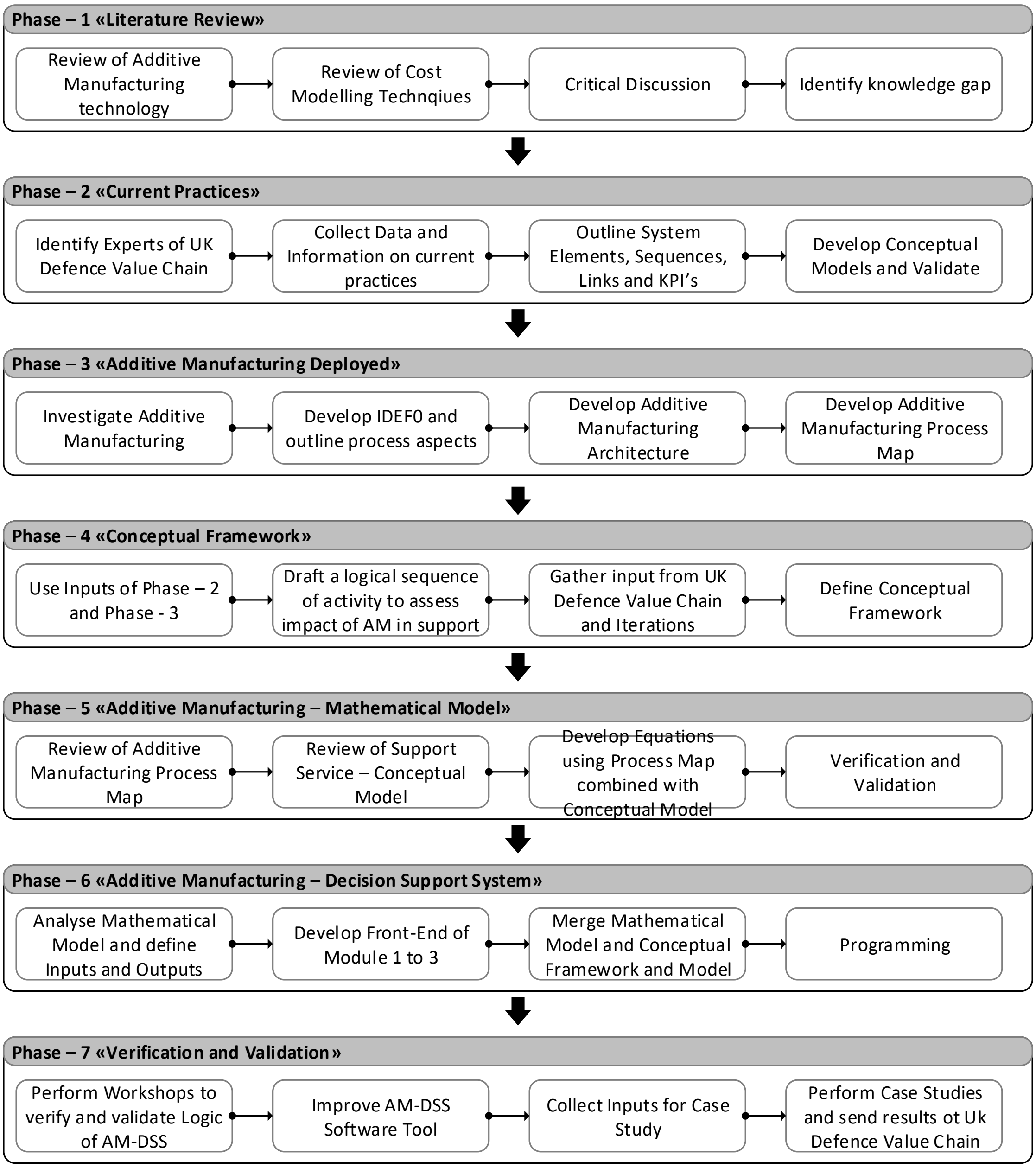


Figure 23 - Research Methodology

The methodology includes various types of research methods such as primary and secondary research, exploratory research, data collection, experts' elicitation and capture and direct observation. In various stages hypothetico deductive approaches have been applied.

3.1 Phase – 1 Literature Review

The PhD has started with a systematic review of the literature on WAAM Technology and "Cost Modelling". This has been carried out through secondary research methods. Reviewing the literature on these aspects allowed the author to gain technical knowledge on the two most important topics of this PhD, AM and Costing Techniques. A critical discussion has been carried out to evaluate the pros and cons of both, AM technologies and estimation techniques.

Finally, the research gap has been identified allowing the author to define better the PhD aim and boundaries of the research and identify its knowledge contributions.

3.2 Phase – 2 Current Practices

Following the literature review, the current practices of Defence Support Services (DS2) have been investigated. With DS2 we refer to Industrial Product Service Systems (IPS2) which undertake as main business the delivery of turn-key support service solutions to complex platforms. This PhD has focused mainly on maritime defence platforms, more specifically the Royal Navy platforms. To carry out this phase of the PhD, key players of the Defence Value Chain have been identified and involved in the primary research activity. Various workshops have been carried out with Ministry of Defence (MoD) Abbey Wood, Defence Equipment & Support (DE&S), Defence Science & Technology Laboratory (DSTL), Department of Defence, Navy Command Headquarters (NCHQ), Small & Medium Enterprise involved in Additive Manufacturing and finally the leading British Defence Support Service provider. The workshops involved an initial presentation on the PhD developments followed by a session on expert's elicitation and capture. Through the elicitation of expert's judgement, it has been possible to obtain reliable data and information related to current practices of defence support services of the Royal Navy. Given the involvement of different organisations located in various stages of the UK Defence Value Chain it has been possible to acquire different perspectives on support service practices. This strategy allowed to obtain very detailed information and an exhaustive overview of the dynamics of support services. Once the data and information has been collected, these have been interpreted and cross checked between each other. Following this, visual models, process maps and schematics have been developed to have a standard simplified version of a "System of Interest" (SoI) of a Defence Support Service (DS2). The System of Interest is made of system boundaries, system elements, links, triggering events, sequences and Key Performance Indicators (KPI) to measure the DS2. Moreover, systematic deduction has been made to define the dynamics of a DS2 describing qualitatively the behaviour of a DS2. The current practices phase represents a foundation of the PhD as it is the part which defines what a support service is, what does it involve, how it delivers value to the Royal Navy and finally what are the options to deliver spares to the Royal Navy. This chapter investigates through a system approach a "Defence Support Services" (DS2). The proposed methodology is based on an adaptation of "Soft System Methodology" (SSM) (Checkland, 2001).

Table 2 - Source of Expertise

Position	Experience	Interviews
Engineering Director	10 years	6 hrs
Technology Acquisition Lead	6 years	6 hrs
In-Service Support Manager	5 years	6 hrs
Defence Equipment and Support Officer (1)	5 years	3 hrs
Defence Equipment and Support Officer (2)	5 years	3 hrs

Soft System Methodology is particularly suitable for enterprise modelling and is used in problem solving processes to structure the analysis and the solution development. The aim of the methodology is to develop conceptual models of support services using system rules. The proposed methodology is based on SSM and has been tailored to better fit the research aim. A mix of qualitative methods such as interviews, observation and deduction has been utilised to carry out the investigation of current practices.

Experts in DS2 have been identified and involved in the research for collecting information and validation of the results.

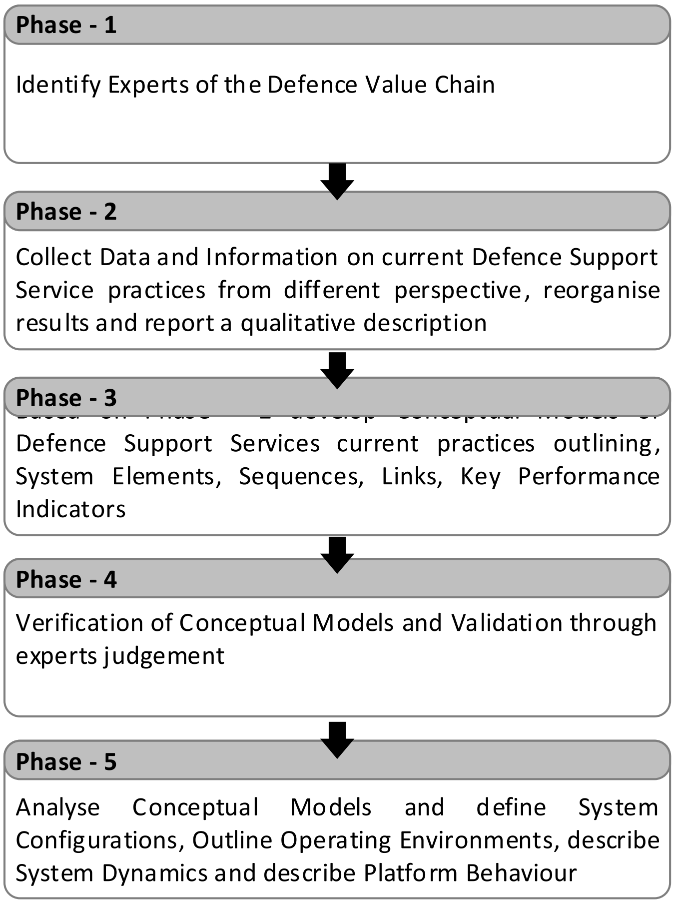


Figure 24 - Research Methodology

“Define the situation and problem”: AM is considered as a promising technology. Especially for DS2 providers given their requirement to operate with disrupted and extended supply chain. AM is particularly suitable for delocalised manufacturing of low to medium volume productions, moreover the technology allows production of any type of geometry without affecting the productivity. The current problem faced, is the inability to assess AM applications in support services practices for the Royal Navy. DS2 are complex systems and a current review of literature outlined that there is a lack of research on AM applications for DS2. Current practices should be investigated and defined.

"Current practices": this is based on primary research and interviews with industrial experts of DS2. The aim of the phase is to develop conceptual models that outline DS2 as systems. The conceptual models need to provide an extensive knowledge of DS2 outlining its elements, the links, the possible scenarios, the operating environment in which they operate and finally a "Key Performance Indicator" (KPI) through which a DS2 can be measured. This will cover a knowledge gap on DS2 literature.

The following questions have been asked during the semi-structured interviews:

- *Can you describe the current practises of Defence Support services to deliver spares to the Royal Navy platforms?*
- *What are the main organisations involved in this activity?*
- *Can you design a process map of current practices outlining System Elements, links, triggering events, sequences, key performance indicators, operating environments of a DS2?*
- *Which are the factors that most influence the availability of systems on the Royal Navy platforms?*
- *Can you describe the behaviour of a Royal Navy platform? What are the phases and what is the impact of these in the performance of delivering the required spares?*

Current practices chapter has been developed through interviews and conceptual modelling. Results have been consequently validated. The sequential phase involved the conceptual framework development, which has been carried out using current practices and results of a critical review published in a journal paper (Busachi et al, 2015).

3.3 Phase – 4 Conceptual Framework

A conceptual framework has been developed to make an exhaustive assessment of the Additive Manufacturing applications in the context of Defence Support Services (DS2). The conceptual framework has been developed using inputs such as the Current Practices results, the investigation of AM deployed and expert's inputs.

The framework has been developed using "Soft System Methodology" (SSM) and through primary research based on unstructured interviews with experts of DS2 firms and MoD. The methodology is outlined in Figure 25 and is made of four phases. Phase 1 consists of the definition of the situation and the problem faced, in this case the emergence of a promising technology, AM and the opportunity to improve the efficiency of the support service system. Phase 2 investigates the current practices, where a system approach has been adopted to define a standard of a DS2, its elements, links, triggering events and key performance indicators. Phase 3 involves the development of the framework, which is based on the analysis of available AM technologies (from a system perspective) and current DS2 practices. Finally, Phase 4 involves the comparison of the current practices with the next generation ones based on AM deployed in the front-end of the support service system.

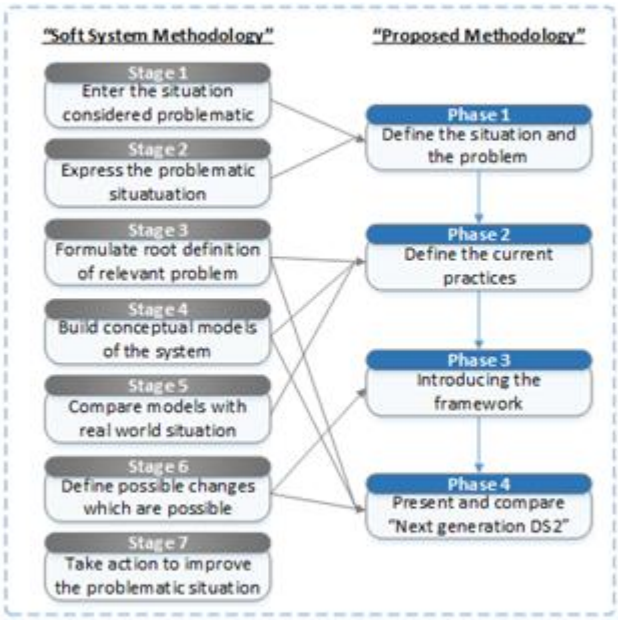


Figure 25 - Methodology

Expertise has been elicited and captured during two workshops which lasted several hours. The results of the workshop have been used to feed a conceptual modelling phase in which the framework has been defined to make an exhaustive and holistic assessment of AM applications in DS2. Finally, the result of the conceptual modelling phase have been verified and validated through expert judgement.

3.4 Phase – 5 Additive Manufacturing Mathematical Models

Additive Manufacturing Mathematical Models are required to model the time, cost and benefits of AM applications in Defence Support Services.

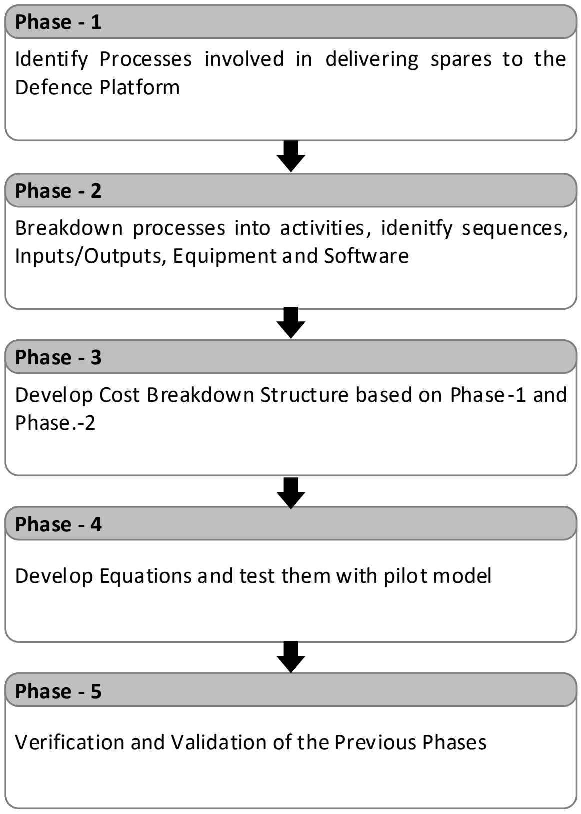


Figure 26 - Methodology

To develop the mathematical models, a hybrid approach has been adopted. Firstly, the System of Interest (SoI), process maps and IDEF0 of Additive Manufacturing and Defence Support Services have been reviewed and analysed. Through this analysis it is possible to identify and quantify the number of activities involved, cycle time of activities, resources consumed such as engineer time, equipment time and software time. Using as inputs these aspects a "Cost Breakdown Structure" (CBS) has been developed and sent to industrial users and academic experts for verification and validation. Three iterations have been carried out to define the CBS and once this has been validated the mathematical models have been developed and the relevant model architecture.

As follows a sequential description of the approach:

- Phase – 5.1 “System of Interest” (SoI): this represents a conceptual modelling activity which seeks to define the boundaries of the investigated system (the AM organisation), its elements, sequences, links, triggering events and dynamics.

- Phase – 5.2 “Business Process Mapping” (BPM): this is the sequential conceptual modelling activity which provides a further level of information on the AM organisation and how it delivers value through its processes.

- Phase – 5.3 “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 which needs to be as detailed as possible on the FDM system.

- Phase – 5.4 “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 within the AM organisation. This phase is based on the work of (Zhai & Lockett, 2012).

- Phase – 5.5 “Model Architecture”: this phase aims at studying and defining the logic of the cost model, 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 to make it functional and adaptable to various organisations.

As follows the list of questions asked during the interview:

- “What are the System Elements of an AM Organisation?”

- “How are the System Elements connected?”

- “What are the triggering events of an AM Organisation?”

- “How is the Supply Chain structured?”

- “What are the macro processes of an AM Organisation to deliver value to customer?”

- “Can you atomise the business processes into distinct activities and display them in a sequence?”
- “Can you outline the inputs/outputs of each activity?”
- “Can you outline the resources consumed during each activity?”
- “Can you outline the min/max cycle time of each activity? What are the factors influencing this variability?”

The results of the interviews have been used collectively to input the development of the SoI and BPM and visual representations have been made and sent to the experts to verify and comment.

3.5 Phase – 6 AM Decision Support System

The Additive Manufacturing – Decision Support System (AM-DSS) integrates the three main developments of the PhD which are also the contributions to knowledge. These are the AM Mathematical Models, the Defence Support Service – System of Interest or conceptual model and the conceptual framework for assessing AM applications in support services. The AM-DSS itself is a secondary contribution to knowledge. The AM-DSS has been developed in Visual Basic programming language using a user friendly Interactive Design Environment (IDE) called Visual Studio. This programming platform has been selected given its versatility, flexibility and ability to develop standalone software tool applications. To develop the AM-DSS, the Conceptual Framework has been analysed and transformed into an algorithm that governs the AM-DSS, inputs and desired outputs have been identified and a relevant AM-DSS Architecture has been developed. The AM-DSS Architecture outlines three main modules, Module – 1 represents the Logistic platforms, Module - 2 represents the Additive Manufacturing Cost & Time estimation and Module - 3 represents the simulation and estimation environment. The Additive Manufacturing – Mathematical Models have been translated into executable codes in Visual Basic and allocated to Module-1 and Module-2. Module – 3, the simulation environments, has been coded using as reference the DS2 – System of Interest. Module – 3 includes also a mathematical model to cover the estimation of "benefits of AM applications". This minor mathematical model refers to the supply chain and availability equation. Three types of programming and coding activities have been carried out in sequence. Firstly, the front-end of the AM-DSS has been programmed including: Inputs and Outputs textboxes and list boxes, moreover a study on data visualisation has been carried out to identify which graphs are better to visualise results to the user. To help the user to input data on logistics, visual models of a complete support service have been included and the same has been carried out in Module – 3 for the System Configurations (SysCos). This allows the user to see the supply chain configuration for each SysCo selection. Secondly a functional code in the back-end has been written to integrate the three modules and feed the graphs during the simulations. Finally, the mathematical equations have been coded into all three modules to perform the estimations on time, cost and benefits of AM applications in Defence Support Services. To verify the functionality of the AM-DSS various tests have been carried out and the results of the equation have been compared with a pilot model developed in Excel.

3.6 Phase – 7 Verification and Validation

This section outlines the validation activity of the AM-DSS, which includes the mathematical models, the conceptual framework and the system of interest previously described in each chapter. Various workshops have been carried out with the MoD, DS2 providers and NCHQ to verify and validate the logic of the AM-DSS. This allowed also to gather feedback on how to improve the software tool in terms of accuracy and outputs level. The validation activity has been carried out as a structured workshop with a set of questions:

1. Is the supply chain module exhaustive? Does it includes the most important activities occurring within a DS2?
2. Is the cost module exhaustive? Does it include the most important costs occurring within an AM deposition?
3. Is the simulation exhaustive? Does it include the most important KPI's of a DS2?

4 Current Practices

4.1 DS2 Systems

This section aims to investigate current practices in DS2 and outline key information on traditional DS2 systems. To do this 5 structured and unstructured interview have been carried out with senior engineers of a leading British DS2 provider.

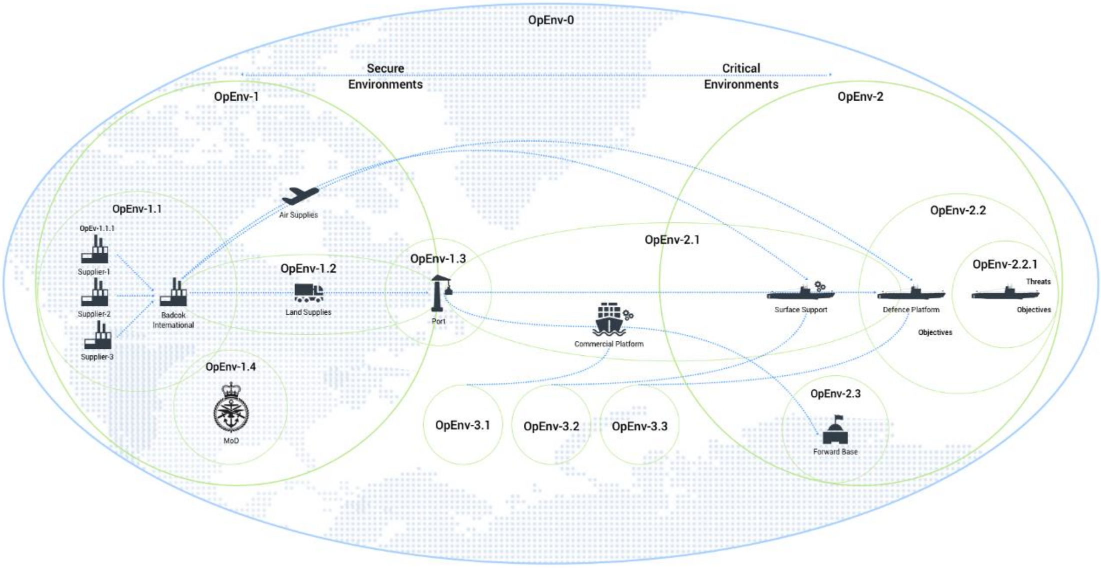


Figure 27 - Conceptual Model of a DS2 (see Appendix – 1)

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.

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. The CES has a sequential behaviour, which is featured with randomness (i.e. Cycle Times may vary).

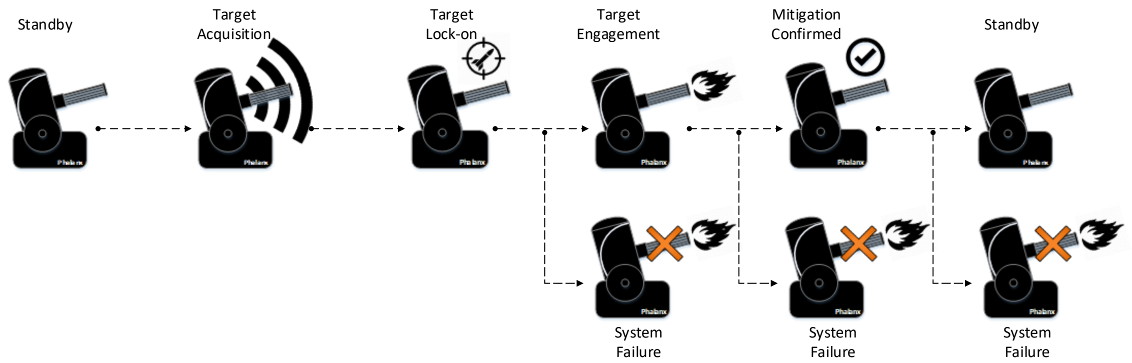


Figure 28 - CES System Dynamics

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.

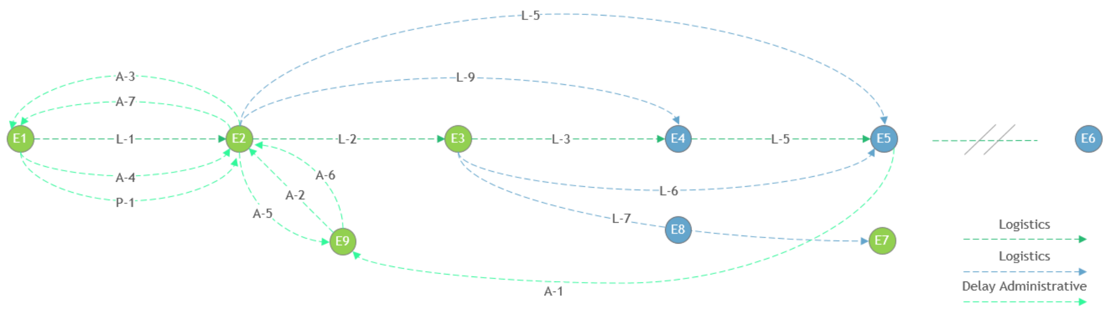


Figure 29 - DS2 Procurement and Delivery (see Appendix – 1)

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.

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 classic 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) submerged support 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 traditional DS2’s SE are strictly linked together and through the interaction between the SE the DS2 is able to support the availability of systems on platforms. As can be deduced, a DS2 is triggered by the change of state of the system. A system has 3 states: 1) Operating, 2) Standby and 3) Down. A system’s state is triggered by the occurrence of events. These events are threats, targets and random failures. When a threat occurs, a system operates to eliminate that threat. When a target is clear, a system operates to hit it. When a system is “Operating” or in “Standby”, the system is available and consequently the DS2 system is in pause. When the system is “Down” the DS2 system is triggered and required to operate to do whatever to restore the availability of the system. 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) (also competences on board). 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). Distance and speed of delivery of component and competences are critical factors to availability.

After validation of the models the authors have carried out analysis through deductions and assumptions. DS2 systems are in fact very complex, a limited number of options have been included following the principle accuracy/effort relationship developed by (Robinson, 2004) which outlines that a highly accurate model might not provide extra value and in fact requires extra effort.

The following sections will cover:

- *"DS2 System Analysis":* a generic DS2 system is outlined, the system's elements and links are described and finally the "Key Performance Indicator" (KPI) of availability is described and equation variables are linked to the DS2 system.
- *"DS2 System Configuration" (SysCo):* outlines all possible scenarios of the supply chain, these represent the option which a DS2 must deliver value to the Royal Navy.
- *"DS2 Operating Environment" (OpEnv):* outlines the operating environments in which a DS2 operates. OpEnv have strict requirements which must be met to accomplish their aims.

The collection of System Analysis, SysCo and OpEnv provide a simplified but exhaustive representation of a traditional DS2 system, its relations and dynamics. Moreover, this collection represents the minimum complexity which should be modelled.

4.2 Systems Analysis

A DS2 provider aims to support complex engineering systems installed on defence platforms. In the case of the Royal Navy, these platforms are aircraft carriers, destroyers, frigates and submarines. The Royal Navy platforms 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 conceptual model represents a DS2 as a system and outlines the end-to-end process of a DS2 to provide value to the Royal Navy. A DS2 system delivers value through the interaction of various system elements (E°) which are connected through links (L°, A° and P°). 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 complex system to achieve its purpose when required to do so.

4.3 Systems Elements

A DS2 is made of nine system elements which can be divided into static elements, active non-critical elements and active critical elements.

Table 3 - System's 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

As previously described, a DS2 system's elements need to interact with each other to deliver value to the Royal Navy. This interaction is given by three links: 1) logistics (L°), 2) Administrative delay (A°) and 3) Procurement delay (P°). These links are therefore critical variables of an expanded equation of Availability. A DS2 provider wants to minimise these values to maximise Availability.

$$A_o = \frac{\boldsymbol{O_t} + S_t}{O_t + S_t + PM_t + CM_t + \boldsymbol{AD_t} + \boldsymbol{PD_t} + \boldsymbol{LD_t}} \quad 3)$$

$$\boldsymbol{O_t = Operating\ Time}$$

$$\boldsymbol{S_t = Setup\ Time}$$

$$\boldsymbol{PM_t} = Planned\ Maintenance\ Time$$

$$\boldsymbol{CM_t} = Corrective\ Maintenance\ Time$$

$$\boldsymbol{AD_t} = Administrative\ Delay\ Time$$

$$\boldsymbol{PD_t} = Procurement\ Delay\ Time$$

$$\boldsymbol{LD_t} = Logistic\ Delay\ Time$$

Given the use of deployable and active platforms, which may operate remotely in the world, a major factor which negatively influences availability is given by the logistic delay time (LDT) and its relation with distance and speed of delivery. To cope with this problem (distance), platforms are featured with small warehouses to keep inventory of critical-to-availability components. Unfortunately, defence platforms have various units of complex systems featured with extended number of sub-systems and components. For example, the "Highly Mechanised Weapon Handling System" (HMWHS) is made of 17 sub-systems with a total of 1500 components. A defence platform does not have enough capacity to keep all the required components to support its systems. Space is a critical and limited resource and is strictly linked with the survivability metric of the platform. As outlined before, distance is a critical variable which is not controllable by a DS2 provider. The main mitigation strategy to cope with distance is the allocation of spares in the front-end of a DS2 system (support vessels or forward bases). This strategy is complex, and requires a large amount of effort and technology to be successful. Moreover, the forecast of failures of components is a highly complex process and given the high level of uncertainties that may lead to inaccurate estimates.

The next section will investigate and explain the Logistic Delay Time (LDT) and the Administrative Delay time (ADT).

4.4 Logistic Delay Time

Logistics Delay Time (LDT) links are outlined in the conceptual model What a DS2 can control, is the responsiveness (given by type of contract, Administrative delay time, inventory levels and Manufacturing lead time of suppliers) and the speed of delivery (given by the Logistics options and transportation type) of a DS2 system through sea, air and land. Generally, the quicker a delivery is, the more expensive it is.

Table 4 - Logistics Links

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.

These logistic links lead to a wider range of options (N°15), which is investigated in “DS2 –System Configurations” (SysCo) later.

4.5 Administrative Delay Time

The Administrative Delay Time (ADT) is an element of traditional spare parts contracts between DS2 providers and MoD. ADT is made of seven links outlined in Figure 2. The ADT sequence is described assuming the rule that spare parts are not available in E2, E3, E4, E5, E6, E7 and E8 (this represents the worst-case scenario given the highest distance).

Table 5 - Administrative Delay links

Tag	Reference	Description
A-1	E5-E9	Defence platform sends the request for a spare part to MoD.
A-2	E9-E2	MoD sends a request for quotation to DS2 provider.
A-3	E2-E1	DS2 provider send request for quotation to supplier.
A-4	E1-E2	Supplier sends DS2 provider price and time of deliver between E1-E2.
A-5	E2-E9	DS2 provider computes its price for spare part and delivery time between E2-E5.
A-6	E9-E2	MoD negotiates with DS2 provider and if successful places order.
A-7	E2-E1	DS2 provider places order to supplier.

The sequence of the ADT is time consuming and not value adding. ADT in “Contracting for Availability” (CFA) is theoretically eliminated or dramatically reduced, improving the overall performance of the DS2 system.

4.6 Traditional DS2 - "System Configurations" (SysCo)

"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, therefore SysCo1 is the fastest and SysCo5 the lowest. It is assumed as a rule that the spare part holder or manufacturer is E1 and there are no available spares in E2, E3, E4, E5, E6, E7, E8 and E9.

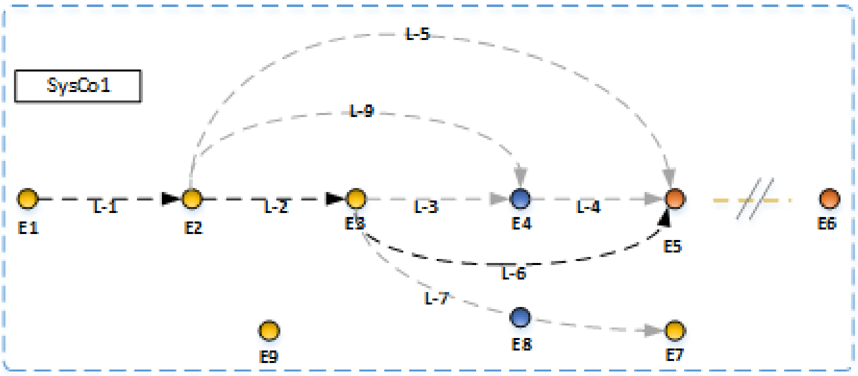


Figure 30 - SysCo1

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.

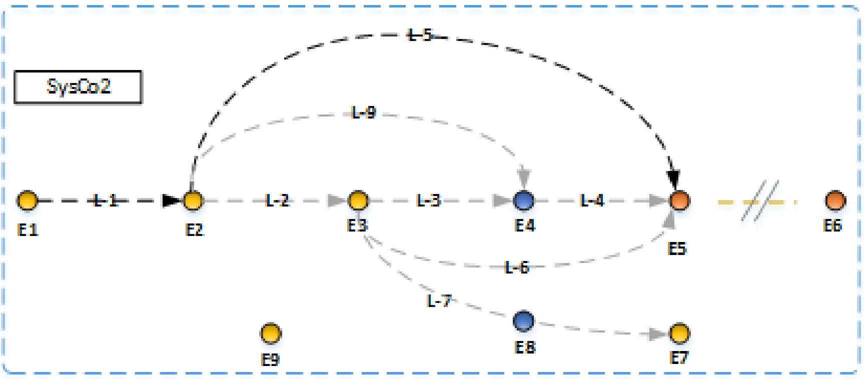


Figure 31 - SysCo2

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.

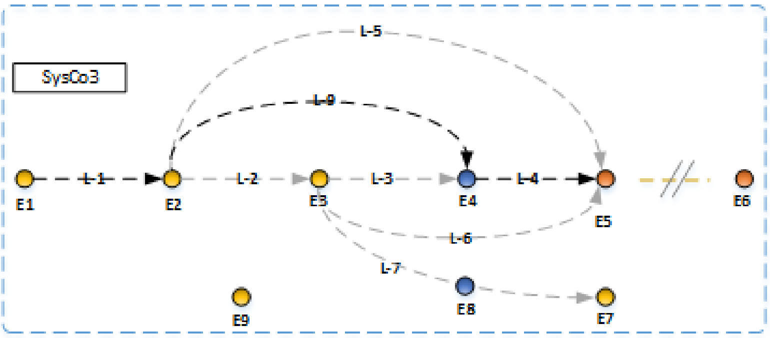


Figure 32 - SysCo3

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, L4 (land, air, sea). L9 and L4 distances are highly variable.

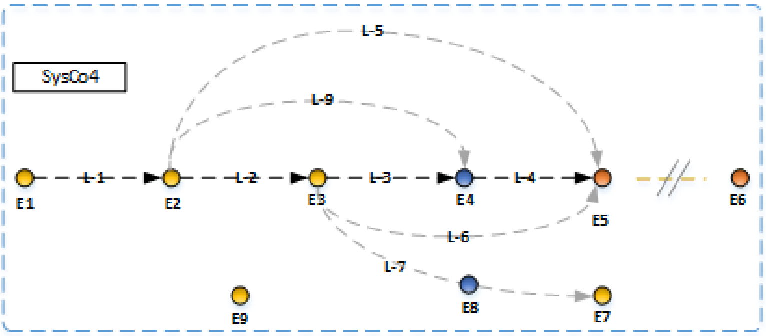


Figure 33 - SysCo4

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

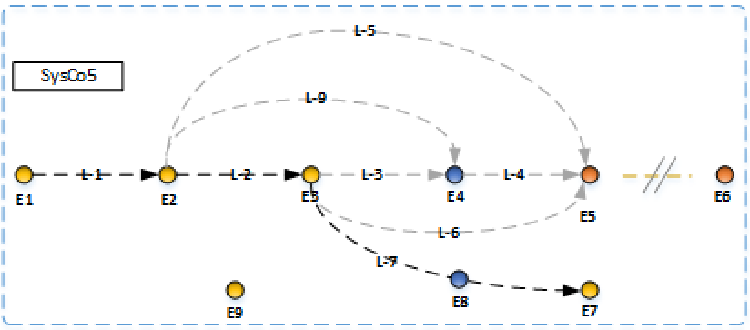


Figure 34 - SysCo5

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. Given the use of commercial vessels this is considered a cheap SysCo and the most commonly used.

As follow Table 6 - SysCo rating

with a recap of SysCo's and relevant rating on cost, speed and security. The scale is from 1 "worst case" to 5 "best case".

SysCo	TAG Sequence	Logistics Type	Cost	Speed
SysCo1	L1, L2, L6	Land, land, port	1	5
SysCo2	L1, L5	Land, air	4	4
SysCo3	L1, L9, L4	Land, air, sea	5	3
SysCo4	L1, L2, L3, L4	Land, land, sea, sea	3	2
SysCo5	L1, L2, L7	Land, land, sea	2	1

Table 6 - SysCo rating

This section investigates the current DS2 practices. The research approach used consisted of carrying out interviews with experts to feed a conceptual modelling phase. The conceptual model developed has been validated by the experts. Afterwards an analysis of the conceptual model has been carried out. The analysis provided an overview of a DS2 system, outlining what are the system elements, what is the flow of the system, what are the triggering events, what are all the possible options of configuration and finally what is the system's performance ratio, and availability. Availability measures are the ability of a system or equipment to perform its function when required to do so. A DS2 system's performance is given by the availability of the system or equipment it supports, the most impacting factors are given by ADT, PDT and LDT. It can be concluded that the owner of the system or equipment to be supported (in defence MoD), wants to maximise availability by reducing ADT, PDT and LDT. Currently the MoD establishes two types of contracts to support its system or equipment, spare parts contract and "Contracting for Availability" (CfA). In the first case the service provider's profits are linked with the number of failing parts. The service provider does not have a financial interest in improving availability and the performance of the DS2 system. In the case of CfA, the service provider agrees with MoD a certain level of availability to be guaranteed over an extended number of years for a certain price. In this case the DS2 provider has strong interest in improving the performance of the DS2 system to reduce its costs and maximise its profitability. With CfA contracts, both the service provider and the MoD have a mutual advantage.

4.7 System Dynamics

Figure 20 outlines the factors which defines the dynamics of a DS2.

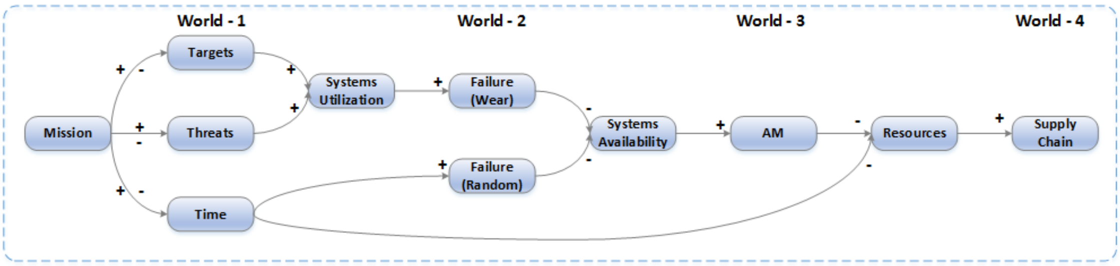


Figure 35 - System Dynamics visualisation

A DS2 is triggered by failures of components. Failures are due to random events or due to systems utilization. The utilization of a system is triggered by the occurrence of threats and by the targets of the mission of the platform. The dynamics of a DS2 can be grouped in to four different classes or worlds which collectively provide an exhaustive representation on how a DS2 is triggered and evolves over time:

- *World1:* represents the external world in which a platform operates. This is given by a mix of controllable and uncontrollable events such as targets, threats and time as duration of a mission. Targets and threats represent the triggering events which influence the whole DS2 system.

- *World2:* represents the systems which allow the platform to be successful and survive. World1 influences the utilization of these systems, the higher the utilization the higher failure rate due to wear. Moreover, failure might be random and the probability of occurrence of random failure is related to the progression of time.

- *World3:* represents the WAAM system (only in next generation DS2), its manufacturing system and its stocks of raw materials. A drop-in Availability triggers the RAS2 which consequently consumes its resources which are limited. In case of current practices this world represents the warehouse where components are held.

- *World4:* represents the supply chain and the logistics of the DS2. The reduction of resources due to the operation of the RAS2 triggers the supply chain to restore its resources.

It can be concluded that the driving factor of a DS2 is the mission of the platform, which will define what will be the behaviour of the platform and consequently the behaviour of the DS2 to support the platform during its mission.

4.8 Defining the behaviour of the Platform

This section investigates the factors which influences and rules a platform's behaviour. Previously it has been outlined that a DS2 system is triggered by failures of system's components.

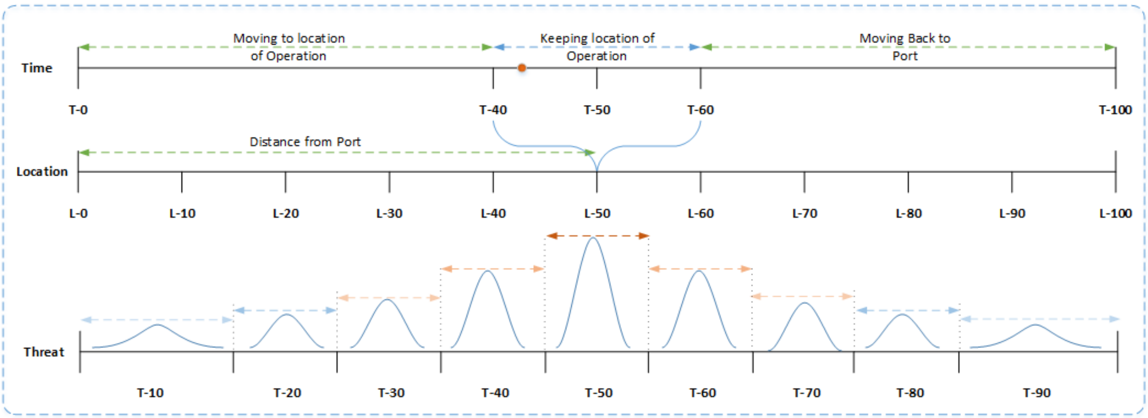


Figure 36 - Factors

When a system's components fail and the related spare part is not held in the platform, the DS2 system is triggered and its SysCo will vary and adapt based on 1) location of the platform and 2) criticality of the component.

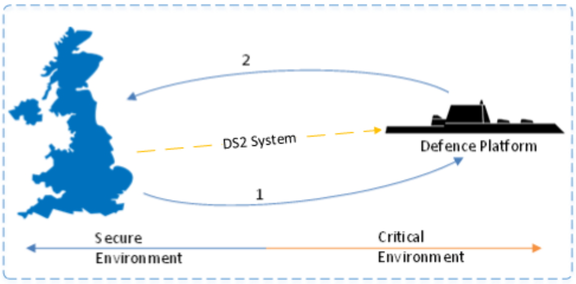


Figure 37 - Mission Loop

The mission of a platform is considered as a loop as outlined in Figure 37 and the DS2 system evolves based on the location of the platform. Failures might be random but are mainly due to the system's utilization which is influenced by platform's behaviour. The platform's behaviour is ruled by four main factors 1) mission aim, 2) mission time, 3) the related location to certain times and 4) related threats associated to that location. The first three factors are internal and known while the fourth factor, "threats" is unknown and given by the reaction of the counterpart to limit or disturb the platform during its mission or to prevent the platform from accomplishing its mission. What is known is that, if the platform's location of operation is in OpEnv2 "War theatre", the probability of occurrence of threats is higher than OpEnv1 "Secure Environment". This is mainly given by the control of the counterpart over the territory. Figure 38, groups together the three factors represented as axis and outlines other critical information which is critical in defining a DS2 behaviour and configuration. The first axis outlines the progression of time with T-0 the beginning of the mission and T-100 the end of the mission. The mission defines a route which the platform must follow to arrive to a "location of operation". The first phase is a transition to the location of operation; the second phase is about holding the location and operate over a period (i.e. from T-40 to T-60) and finally the third phase is the transition of the platform back to the port or to another friendly port. Figure 38 outlines that to each point of the first axis relates a point on the second axis "Location".

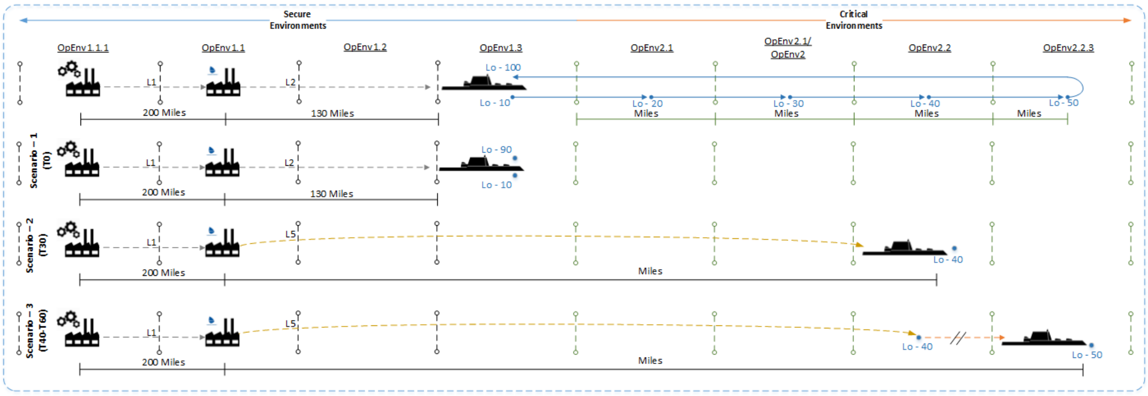


Figure 38 - DS2 evolution over mission time

The Location axis defines in which OpEnv the platform is situated with a related distance from OpEnv1 “Secure Environment” where the DS2 facilities are located. The distance between OpEnv1 and the location of the platform is a critical measure as it defines the way a DS2 system can deliver the component with its SysCos. Moreover, the criticality of the component plays a crucial role in defining the speed of delivery. If a component is considered highly critical for mission and safety this will be delivered through SysCo2 or “air deployment” (threats not considered). Finally, the third axis outlines the probability of occurrence of threats. The probability grows with the progression to OpEnv2 “War theatre” and achieves its maximum in OpEnv 2.2.3 “Battle theatre”. In this situation, the supply chain is disrupted given the high level of threats. Threats play also a determinant role in the SysCo selection as the support platform which delivers the spares is subject to threats as well. To outline the evolution of a DS2 system in relation to mission time an example has been outlined in Figure 39 which assumes that the platform is in OpEnv1.3 and must reach OpEnv2.2.3 and return to OpEnv1.3. Speed, transitions, time of position hold and threats are not considered. Moreover, the platform has no intermediate support (forward base or support vessel), the spares must be delivered as quickly as possible. Three scenarios have been outlined: scenario-1 time of mission is T0 and related location is Lo-10 in the port, the related SysCo is SySco1 with land delivery. Once the mission starts and progress over time the SysCo will evolve and adapt based on the requirements of the situation. Scenario-2 the time of mission is T30 and related location is Lo-40 in OpEnv2.3 “operation theatre”. The related SysCo is SySco2 with air delivery. The platform can be supported as OpEnv2.3 is featured with a stable supply chain. Finally, in scenario-3 the mission has reached T40 and the platform is located within OpEnv.2.2.3 “Battle theatre” which cannot be served by a DS2 system as the supply chain is disrupted. Therefore, the spares can be delivered only in OpEnv2.2.

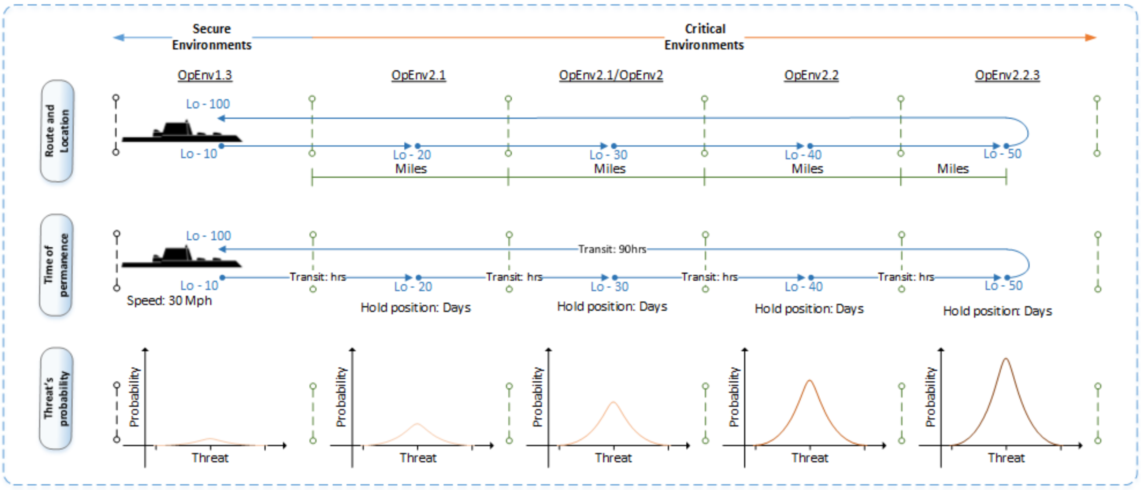


Figure 39 - Speed and times of hold

Finally, Figure 39 outlines more information related to the time of transition between a location and the other and the time that the platform holds the position. As stated previously we assume that the probability of occurrence of threats increases with the progression to OpEnv2.2.3. Moreover, must be outlined the total time spent in each OpEnv. This is given by the speed of the platform, the route of the mission and the requirements of the mission. The more a platform operates within an OpEnv the more it is likely to be subject to the occurrence of threats.

4.9 Validation of Current Practices results

This section outlines the validation activity for Chapter – 4 “Current Practices of Defence Support Service”. As follow the list of the experts involved in the validation activity.

Table 7 - Experts for Validation

Tag	Position	Experience	Organisation
1	**Technology Acquisition Lead**	8 years	Support Service provider
2	**Business Development**	25 years	Support Service provider
3	**Director of Engineering**	25 years	Support Service provider
4	**Head of Bids**	22 years	Support Service provider
5	**Director of Support**	40 years	Support Service provider
6	**Head of Capability**	30 years	Support Service provider
7	**Captain RN**	Lots	The Royal Navy
8	**Innovation Program Manager**	14	The Royal Navy
9	**Engineering Officer**	17	The Royal Navy
10	**Mechanical Engineer**	1	MoD's Contractor
11	**Thermal Analysis Specialist**	30	MoD's Contractor
12	**Systems Engineer**	35	MoD's Contractor
13	**Future Concepts**	9	MoD's Contractor
14	**Materials Engineer**	16	MoD's Contractor

Is the Conceptual Model of current practices accurately described? Does it include the most important activities occurring within a Defence Support Service?

Strongly Disagree	Disagree	Fair	Agree	Strongly Agree
		3,6	1,2,4,7,8,9,10,11,12,13,14	5

5 ADDITIVE MANUFACTURING – MATHEMATICAL MODELS

5.1 Introduction and Research Methodology

This chapter aims at representing the Additive Manufacturing Mathematical Model and outline the development approach. The mathematical model represents one of the three contributions to knowledge developed during the PhD. These are embedded in the Additive Manufacturing – Decision Support System (AM-DSS) and are employed for estimating the Product Cost and Lead Time of a component printed with Additive Manufacturing. Being able to be estimate the time and cost of Additive Manufacturing are key elements for carrying out a comparison with traditional support service solutions and outline also the benefits of AM application in this sector. Additive Manufacturing – Process Maps. To obtain a further level of information regarding the value creation process of the AM Organisation, a process analysis has been carried out and presented in the form of a Process Map outlined in Figure 40. The process analysis outlined that the AM Organisation is made of 3 interconnected processes: 1) Bidding Process, 2) Geometric Process and 3) Manufacturing Process.

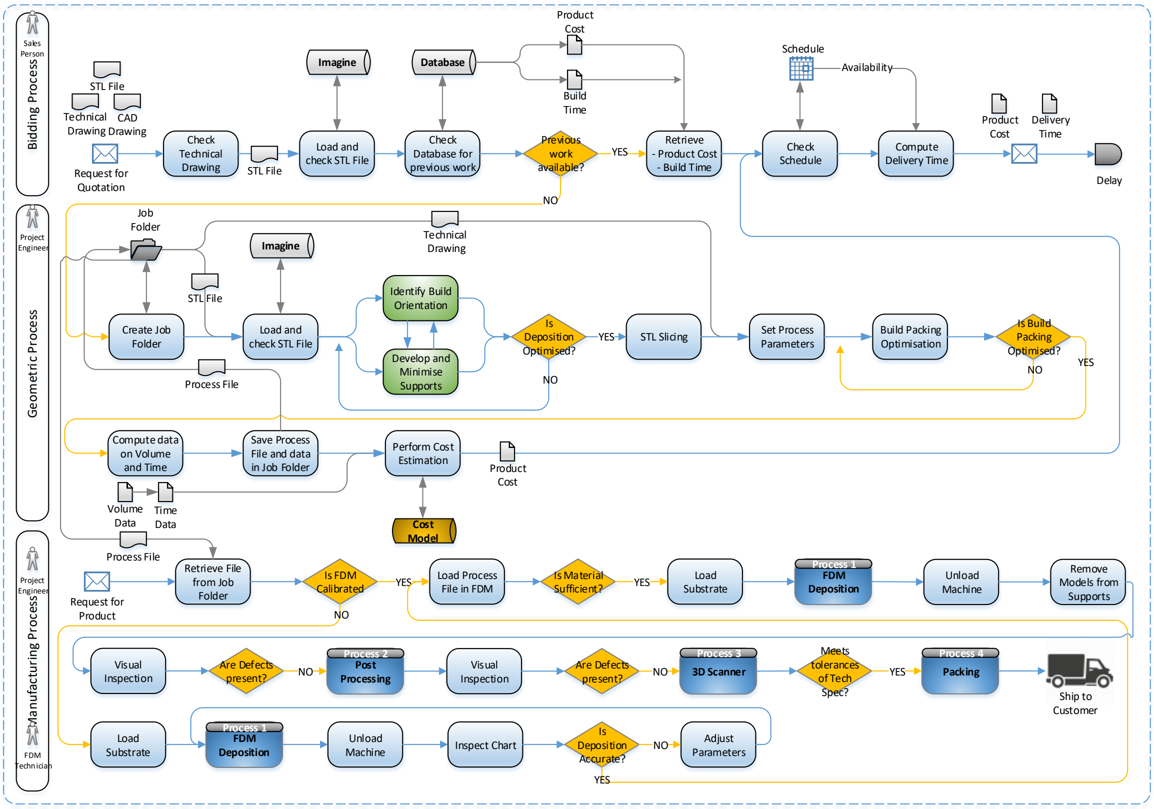


Figure 40 - Additive Manufacturing Process Map

The Process Map has been developed to atomize the business processes into the necessary sequential activities. Moreover, this type of documents provides an extensive number of information such as INPUTS/OUTPUTS, responsibility of activities, necessary resources, decisions and scenarios.

5.1.1 Bidding Process

This process is featured by seven sequential activities and is triggered by the "Request for Quotation" (RFQ). A Sales persona and an Engineer with FDM experience is responsible to carry out all the activities. The Engineer is supported by an "Additive Manufacturing" (AM) software which can read STL files which contains the data on the geometry. The aim of the process is to provide customers with two key decision variables: lead time and product price. Based on these two variables the customer will draw its decision on placing an order or select another supplier. If a geometry has been processed before by the engineer, the data on product cost and price are already available on a database. If the geometry has not been processed before the engineer must go through the geometry preparation process to complete the bidding process.

5.1.2 Geometry Preparation Process

This process is made of nine sequential activities and is triggered by the need to retrieve data on product volume and time of deposition. The process has two aims, prepare an STL to control an FDM deposition and obtain an early estimate on product cost. Key activities are: build orientation identification, development and minimization of supports and finally cost estimation. These activities do not have standard cycle times and vary significantly.

5.1.3 Manufacturing Process

This process is made of three main sub-processes and eleven activities. The sub-processes are FDM process, post-processing and 3D scanning. The deposition process is triggered by the arrival of the order by the customer. It should be outlined that the FDM machine has to be calibrated for each build.

5.1.4 Scenarios Development

Through the interviews with experts, it was possible to develop two scenarios that occur within an AM Organisation and outline the worst case and best case for each of them.

- Scenario 1 – "previous experience is available": an STL file has been already processed and is stored and available for printing. Cost and cycle times have been already computed therefore the Sales person has only to compute the delivery time through the interrogation of the schedule of the machine. Should be outlined that prices might have to be adjusted to changes in the macro environment (i.e. material cost increment).
- Best Case Scenario: 30 minutes
- Worst Case Scenario: 40 minutes

➢ Scenario 2 – “previous experience is not available”: the engineer has not processed the STL file before; therefore, he has to complete the geometry preparation process. Cycle times may vary dramatically based on project complexity.

- Best Case Scenario: 60 minutes
- Worst Case Scenario: 175 minutes

5.2 Cost Breakdown Structure (CBS)

This section aims to define and present the desired “Cost Breakdown Structure” (CBS) at a conceptual level. The CBS is the Model Output which has to be as detailed and comprehensive as possible. The CBS has been developed through logical inferences and analysis of the combined SoI and BPM. The CBS outlined in Figure 41, presents 17 cost elements which occur within an AM Organisation, which added together represent the Total Cost of the end-to-end process of delivering value to customer.

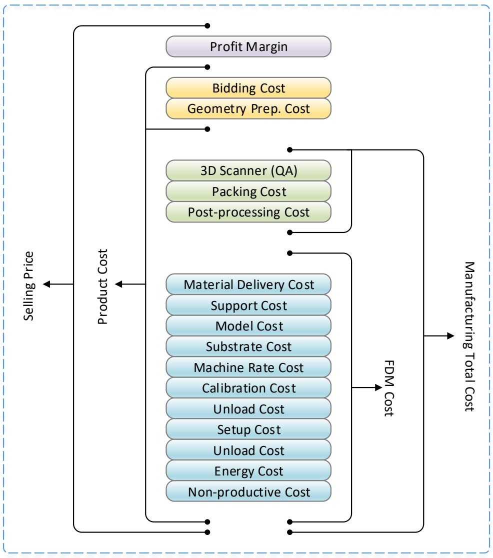
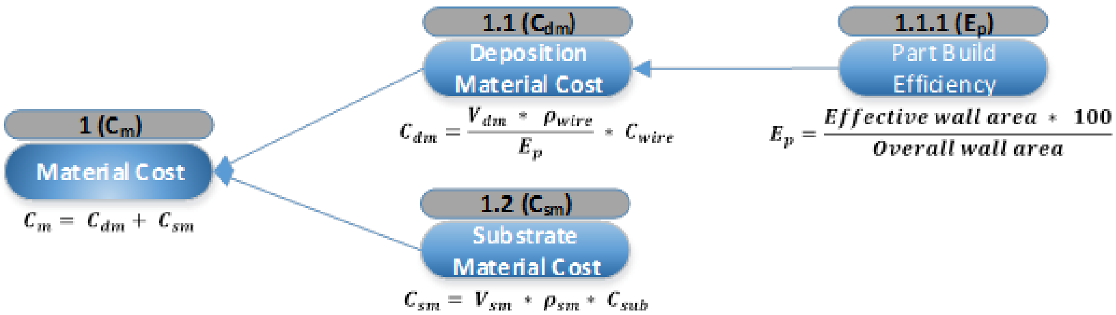


Figure 41 - Cost Breakdown Structure

The CBS is made of the cost of bidding, the cost of preparing the geometry for AM and the cost to manufacture it. While the cost of bidding and the cost of preparing, the geometry have been included at a high level, the cost of manufacturing has been atomised. This has been made to gather the highest level of detail possible focusing especially on the FDM system. 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 customer. To obtain the desired CBS as a Model Output, resources consumed during the activities/processes must be identified, the hourly rate of the initial investment in equipment, software and personnel have to be computed based on expected yearly utilisation, finally Cycle Times (CT) have to be identified.

5.3 Mathematical Models

The following equations have been developed based on Zhai & Lockett, (2012). As follow partial results of the mathematical modelling activity for WAAM technology. Figure 42 - Material Cost outlines the equation to quantify the cost of the material deposited, the substrate and the wasted material which is removed consequently.



$$C_m = C_{dm} + C_{sm}$$

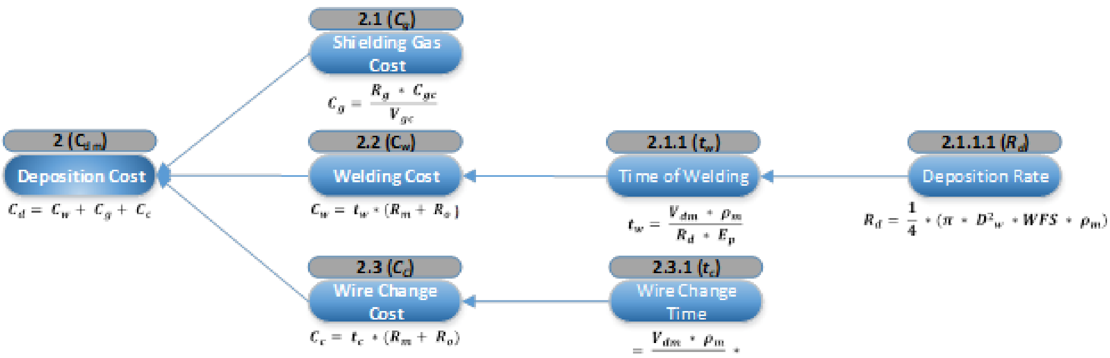
$$C_{dm} = \frac{V_{dm} * \rho_{wire}}{E_p} * C_{wire}$$

$$E_p = \frac{Effective\ wall\ area * 100}{Overall\ wall\ area}$$

$$C_{sm} = V_{sm} * \rho_{sm} * C_{sub}$$

Figure 42 - Material Cost

Figure 43 - Deposition Cost collects all the cost occurring during the deposition which takes into account for utilities, change of wire and machine hourly rate.



$$C_d = C_w + C_g + C_c$$

$$C_g = \frac{R_g * C_{gc}}{V_{gc}}$$

$$C_w = t_w * (R_m + R_o)$$

$$t_w = \frac{V_{dm} * \rho_m}{R_d * E_p}$$

$$R_d = \frac{1}{4} * (\pi * D^2_w * WFS * \rho_m)$$

$$C_c = t_c * (R_m + R_o)$$

$$= \frac{V_{dm} * \rho_m}{} *$$

Figure 43 - Deposition Cost

Moreover costs related to manufacturing activities for setting up the system and unloading the components have been developed. Also, costs related to geometry preparation have been modelled but not included as it is assumed that the robot codes are already ready, stored in a database and geometry preparation has occurred previously.

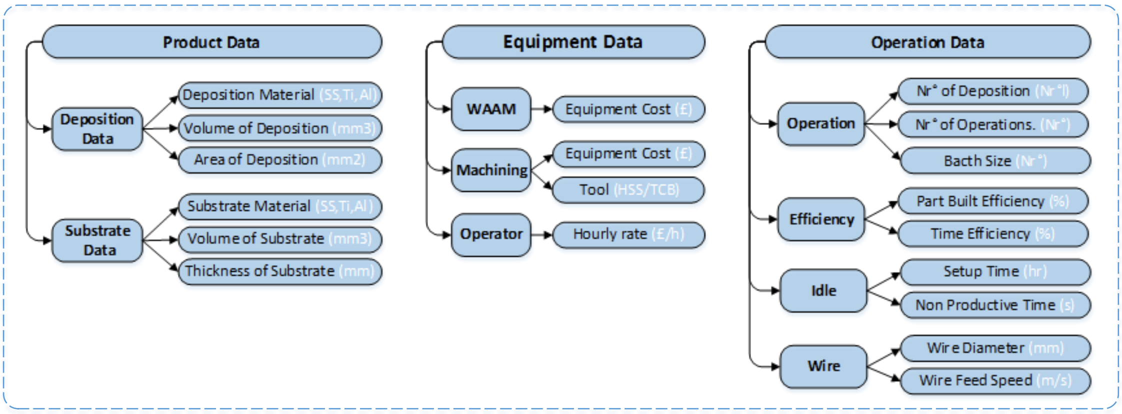


Figure 44 - DSS Logic – INPUT

This phase consists in understanding the INPUTS and OUPUTS of the model and how to create the "Graphical User Interface" (GUI). Figure 44 - DSS Logic – INPUT outlines what inputs are required to feed the equations. As the model requires a wide range of inputs, some of these are set to standard values but can be modified in order to adapt the model to various organisations.

5.3.1 Module 1 – Logistic Platforms

The following equation is used to model the hourly rate of a logistic platform

$$Plat_{rate} = \frac{\frac{Plat_{inv}}{Tim_{uti}*Rat_{uti}}+Plat_{mai}+Ope_{cos}}{Pay_{loa}+Year_{hours}} \quad 4)$$

Where:

$\boldsymbol{Plat_{rate}} = Platform\ Rate$

$\boldsymbol{Plat_{inv}} = Platform\ Investment$

$\boldsymbol{Tim_{uti}} = Time\ of\ Utilisation$

$\boldsymbol{Rat_{uti}} = Rate\ of\ Utilisation$

$\boldsymbol{Plat_{mai}} = Platform\ Maintenance$

$\boldsymbol{Ope_{cos}} = Operating\ Cost$

$\boldsymbol{Pay_{loa}} = Pay\ Load$

$\boldsymbol{Year_{hours}} = Yearly\ Hours$

5.3.2 Module 2 – Additive Manufacturing Technology

The following equation is used to model the hourly rate of an engineer

$$Eng_{rat} = \frac{Gross_{Sal} * (1 - Sal_{con})}{Year_{hours}} * Eng_{Ov} \qquad 5)$$

Where:

$\boldsymbol{Eng_{rate}} = Engineering\ Rate$

$\boldsymbol{Gross_{sal}} = Gross\ Salary$

$\boldsymbol{Sal_{con}} = Salary\ Contribution$

$\boldsymbol{Eng_{ov}} = Engineer\ Overheads$

$\boldsymbol{Year_{hours}} = Yearly\ Hours$

The following equation is used to model the WAAM System rate

$$WAAM_{rat} = \frac{\frac{WAAM_{inv}}{Tim_{uti}} * Uti_{rat}}{(1 - Ov)} \qquad 6)$$

Where:

$\boldsymbol{WAAM_{rat}} = WAAM\ Rate$

$\boldsymbol{WAAM_{inv}} = WAAM\ Investment$

$\boldsymbol{Tim_{uti}} = Time\ of\ Utilisation$

$\boldsymbol{Uti_{rat}} = Rate\ of\ Utilisation$

$\boldsymbol{Ov} = Overheads$

The following equation is used to model the Machining System rate

$$Mach_{rat} = \frac{\frac{Mach_{inv}}{Tim_{uti}} * Uti_{rat}}{(1-Ov)} \quad 7)$$

Where:

$\boldsymbol{Mach_{rat}} = Machining\ Rate$

$\boldsymbol{Mach_{inv}} = Machining\ Investment$

$\boldsymbol{Tim_{uti}} = Time\ of\ Utilisation$

$\boldsymbol{Uti_{rat}} = Rate\ of\ Utilisation$

$\boldsymbol{Ov} = Overheads$

The following equation is used to model the Software rate

$$Sof_{rat} = \frac{Sof_{inv}}{Tim_{uti}} * Uti_{rat} \quad 8)$$

Where:

$\boldsymbol{Sof_{rat}} = Software\ Rate$

$\boldsymbol{Sof_{inv}} = Software\ Investment$

$\boldsymbol{Tim_{uti}} = Time\ of\ Utilisation$

$\boldsymbol{Uti_{rat}} = Rate\ of\ Utilisation$

The following equation is used to model the welding cost:

$$Weld_{Cost} = \frac{V_{dep} * Mat_{den}}{Build_{eff}} * \pi * {Wire_{diam}}^2 * WFS * Mat_{den} * (WAAM_{rat} + Eng_{rat}) \quad 9)$$

Where:

$\boldsymbol{Weld_{cost}} = Welding\ Cost$

$\boldsymbol{V_{dep}} = Volume\ of\ Deposition$

$\boldsymbol{Mat_{den}} = Material\ Density$

$\boldsymbol{Build_{eff}} = Build\ Efficiency$

$\boldsymbol{Wire_{diam}} = Wire\ Diameter$

$\boldsymbol{WFS} = Wire\ Feed\ Speed$

$\boldsymbol{Mat_{den}} = Material\ Density$

$\boldsymbol{WAAM_{rat}} = WAAM\ Rate$

$\boldsymbol{Eng_{rat}} = Engineer\ Rate$

The following equation is used to model the cost of the deposited material

$$DepMat_{cost} = \frac{V_{dep}}{Build_{eff}} * Wire_{den} * Wire_{cos} \qquad 10)$$

Where:

$\boldsymbol{DepMat_{cost}} = Deposited\ Material\ Cost$

$\boldsymbol{V_{dep}} = Volume\ of\ Deposition$

$\boldsymbol{Build_{eff}} = Build\ Efficiency$

$\boldsymbol{Wire_{den}} = Wire\ Density$

$\boldsymbol{Wire_{cost}} = Wire\ Cost$

The following equation is used to model the substrate cost

$$SubMat_{cost} = V_{sub} * Sub_{den} * Sub_{cos} \qquad 11)$$

Where:

$\boldsymbol{SubMat_{cost}} = Substrate\ Material\ Cost$

$\boldsymbol{V_{sub}} = Volume\ of\ Substrate$

$\boldsymbol{Sub_{den}} = Substrate\ Density$

$\boldsymbol{Sub_{cost}} = Substrate\ Cost$

The following equation is used to model the cost of the shielding gas

$$Gas_{cost} = \frac{Gas_{rat} * Gas_{co}}{Cil_{vol}} * Weld_{tim} \qquad 12)$$

Where:

$\boldsymbol{Gas_{cost}} = Shileding\ Gas\ Cost$

$\boldsymbol{Gas_{rat}} = Gas\ Rate$

$\boldsymbol{Gas_{co}} = Gas\ Cost$

$\boldsymbol{Cil_{vol}} = Cilinder\ Volume$

$\boldsymbol{Weld_{tim}} = Welding\ Time$

The following equation is used to model the non-productive cost

$$NonProd_{cos} = NPT_{weld} * (WAAM_{rat} + Eng_{rat}) * Dep_{num} + NPT_{mac} \qquad 13)$$

Where:

$\boldsymbol{NonProd_{cos}} = Non\ Productive\ Cost$

$\boldsymbol{NPT_{wled}} = Non\ Productive\ Time\ Welding$

$\boldsymbol{NPT_{mac}} = Non\ Productive\ Time\ Machining$

$\boldsymbol{WAAM_{rat}} = WAAM\ Rate$

$\boldsymbol{Eng_{rat}} = Engineer\ Rate$

$\boldsymbol{Dep_{num}} = Number\ of\ Depositions$

The following equation is used to model the setup cost

$$Set_{cos} = \frac{T_s}{B_s} * (WAAM_{rat} + Eng_{rat}) + \frac{T_s}{B_s} * (Mac_{rat} + Eng_{rat}) * Mac_{num} \qquad 14)$$

Where:

$\boldsymbol{Set_{cos}} = Setup\ Cost$

$\boldsymbol{T_s} = Time\ of\ Setup$

$\boldsymbol{B_s} = Batch\ Size$

$\boldsymbol{WAAM_{rat}} = WAAM\ Rate$

$\boldsymbol{Eng_{rat}} = Engineer\ Rate$

$\boldsymbol{Mac_{rat}} = Machining\ Rate$

$\boldsymbol{Mac_{num}} = Number\ of\ Machining\ Operations$

The following equation is used to model the time of welding

$$Wel_{tim} = \frac{V_{dep} * Mat_{den}}{Build_{eff}} * \pi * Wire_{diam}{}^{2} * WFS * Mat_{den} \qquad 15)$$

Where:

$\boldsymbol{Wel_{tim}} = Welding\ Time$

$\boldsymbol{V_{dep}} = Volume\ of\ Deposition$

$\boldsymbol{Mat_{den}} = Material\ Density$

$\boldsymbol{Build_{eff}} = Build\ Efficiency$

$\boldsymbol{Wire_{diam}} = Wire\ Diameter$

$\boldsymbol{WFS} = Wire\ Feed\ Speed$

5.3.3 Module 3 – Support System Simulation

The following equation is used to model the travel time

$$TT = Log_{dist}/Plat_{spee} \quad 16)$$

Where:

$\boldsymbol{TT} = Travel\ Time$

$\boldsymbol{Log_{dist}} = Logistic\ Distance$

$\boldsymbol{Plat_{spee}} = Platform\ Speed$

The following equation is used to model the cost of the service

$$Ser_{cos} = TT * Plat_{rat} \quad 17)$$

Where:

$\boldsymbol{Ser_{cos}} = Service\ Cost$

$\boldsymbol{TT} = Travel\ Time$

$\boldsymbol{Plat_{rat}} = Platform\ Rate$

The following equation is used to model the logistic delay time

$$LDT_{CP} = TT_1 + TT_2 + TT_3 \ldots \quad 18)$$

Where:

$\boldsymbol{LDT_{CP}} = Logistic\ Delay\ Time\ (current\ practices)$

$\boldsymbol{TT_1} = Travel\ Time - Section\ 1$

$\boldsymbol{TT_2} = Travel\ Time - Section\ 2$

$\boldsymbol{TT_3} = Travel\ Time - Section\ 3$

The following equation is used to model the service cost:

$$Serv_{cos} = ServCos_1 + ServCos_2 + ServCos_3 \quad 19)$$

Where:

$\boldsymbol{Serv_{cos}} = Service\ Cost$

$\boldsymbol{ServCos_1} = Service\ Cost - Section\ 1$

$\boldsymbol{ServCos_2} = Service\ Cost - Section\ 2$

$\boldsymbol{ServCos_3} = Service\ Cost - Section\ 3$

The following equation is used to model the availability

$$Av_{cp} = \frac{MTBF}{MTBF + ADT + PDT + LDT} \qquad 20)$$

Where:

$\boldsymbol{Av_{cp}} = Availability - Current\ Practices$

$\boldsymbol{MTBF} = Mean\ Time\ Before\ Failures$

$\boldsymbol{ADT} = Administrative\ Delay\ Time$

$\boldsymbol{PDT} = Procurement\ Delay\ Time$

$\boldsymbol{LDT} = Logistic\ Delay\ Time$

The following equation is used to model the downtime:

$$Do_{tim} = ADT + PDT + LDT \qquad 21)$$

Where:

$\boldsymbol{Do_{tim}} = Down\ Time$

$\boldsymbol{ADT} = Administrative\ Delay\ Time$

$\boldsymbol{PDT} = Procurement\ Delay\ Time$

$\boldsymbol{LDT} = Logistic\ Delay\ Time$

5.4 AM-DSS Limitation

Through logical inferences on previous knowledge developed and expert's input, a list of limitations on the model has been outlined in Table - 8. This refers to what aspects of the complexity of real world are not within scope of the model.

Table 8 - Model's Limitations

Aspect	Description
Geometry Complexity	The complexity of the design has an impact on the time of deposition due to increased movement of the deposition nozzle to deposit the features. To model this, a sophisticated algorithm must be modelled to estimate the impact on the complexity on the deposition time.
Part Orientation	The orientation of the part has an impact on the time of deposition due to the related support volume. Designers are instructed to orientate the part to minimise the time of deposition nevertheless this is not always possible, for example when mechanical properties have to be ensured.
Deposition Time Estimation	An equation would be required in order to estimate the time of deposition having as input the volume of material. Moreover, geometry complexity and part orientation should be taken in consideration.
Build Rules	In the BPM the process to prepare the geometry has been outlined and represented as a right-the-first-time process. Nevertheless, in most cases the process is performed various times in order to minimise support volume and improve the deposition time.
Build Failures	Build failures may occur resulting in loosing time and cost. This should be included nevertheless there is a lack of data of failure rates.
Wire Change	During a deposition the wire might deplete and an operator should replace it. Nevertheless, this is dependent on the part volume and the level of the canister and a standard case is difficult to define.
Comparison	The model output does not compare the results with traditional ways of manufacturing omitting important information to carry out a comparison and provide meaningful insight to the decision makers.
Build Chamber Utilisation	It is reporter by users that higher degree of utilisation of the build chamber have a positive impact on the time of deposition as the deposition efficiency increases.
Supplementary Software	Software involved in the geometry preparation process should be included as these have an impact on the product cost.
3D Scanning	Activities related to the 3D Scanner should be modelled as these might consume time. Moreover, the processing time of the acquired data through the 3D Scanner might be higher than the actual acquisition. Finally, the 3D Scanner might not be used in all cases therefore this should be an option in the model.

Moreover, in the BPM two scenarios have been outlined which considers if previous experience is available or not. In case previous experience is available, it means that the company has already performed a geometry preparation for that part, therefore this should not be included totally in the estimate. A rate of the geometry preparation process should be computed based on expected yearly demand and included in the estimate.

6 Conceptual Framework

6.1 Introduction

The following chapter aims to present a framework for assessing the impact and supporting the implementation of the AM technology within the Defence sector. The framework is made up of 8 mutually exclusive phases which collectively provide the decision makers an exhaustive analysis of the impact of the AM implementation. As follows, DS2, AM and the framework are presented and explained.

DS2 providers have the capability to deliver the availability of their own or third party systems/equipment to their customer, in this case the Royal Navy. The Royal Navy operates in mission and safety critical environments through the deployment of its platforms. These platforms such as the Type 45 destroyer, Type 23 frigate and the Astute Class submarine are featured with an extended number of sophisticated and complex engineering systems which allows the platforms to deliver its capability and survive in critical and potentially hostile environments. For the Royal Navy, the availability of its complex engineering systems is a critical factor which is measured through uptime over total time. The most influential elements of the availability ratio are given by the “Administrative Delay Time” (ADT) and the “Logistic Delay Time” (LDT).

Through the exploitation of AM, DS2 can explore new solutions to support the Royal Navy’s complex engineering system. The main idea is to improve the efficiency of the overall service system by eliminating the ADT and LDT through the delocalisation of AM in the front-end of a DS2 system. This solution allows manufacturing the required component next to the point of use. “Additive Manufacturing” (AM) is a disruptive technology which benefits from design freedom, short manufacturing lead times, low buy-to-fly ratios, complexity for free and requires limited space for operating. It can be used for both, printing new components and repair broken ones (if combined with machining and 3D scanner). Moreover, the technology has the potential to reduce or eliminate sub-assemblies, access to new geometries and improve the performance of components. AM from a production perspective is lean, it benefits from “pull” and “just-in-time” moreover the technology can process random geometries without any impact on setups. Given the limited space requirements by AM, mini-factories can be developed within containers and deployed in forward bases in order to reduce the distance to the point of use. This allows to eliminate the planning of components required (forecasted) and produce only what is required in the battlefield. Mini-factories can be developed also for in-platform deployment which will eliminate the LDT. Furthermore “Wire + Arc Additive Manufacturing” (WAAM) is an AM technology which is not present in international standards but it is considered the most promising technology for industrial applications. Firstly it is a wire based technology which implies no health and safety issues compared with powder solutions, easy material feed, medium cost of wire, 100% material efficiency. Featured with high deposition rates (kg/h), low BTF ratios (2), low cost of investment (max £200k), high energy efficiency (90%), good accuracy (1-2 mm), low product cost and manufacturing lead times (hrs), the deposition occurs out of the chamber with unlimited size constraints and lower space required. This technology also benefits from good design freedom and topological optimisation opportunity, good mechanical properties and microstructure (rolling) and no porosity. WAAM is intended for large, fully dense functional components.

6.2 Conceptual Framework

The framework, outlined in Figure 45 has been implemented into a “Decision Support System” (DSS) tool which aims to support critical managerial and technical decision making on the acquisition and implementation of Additive Manufacturing in the Defence Support Service sector. The DSS aims to simulate different system configurations available and outline the level of “Key Performance Indicators” (KPI) such as time, cost and benefits. The simulations outlined the following aspects have been observed: 1) AM can be deployed in a defence platform, a support vessel or a forward base. The impact of AM in DS2 is substantial; firstly it improves dramatically the efficiency of the support to availability of CES, given the elimination of the “Administrative Delay Time” (ADT), “Logistic Delay Time” (LDT) and “Procurement Delay Time” (PDT).

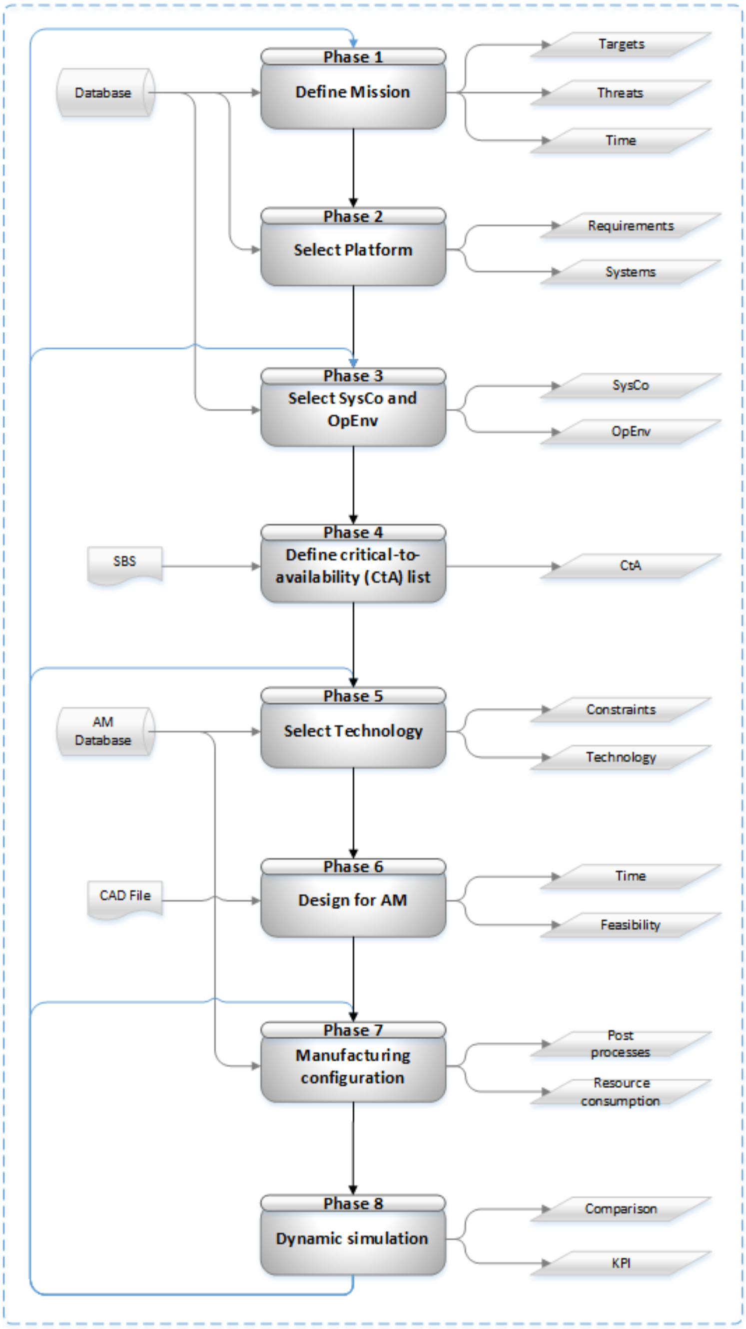


Figure 45 - Conceptual Framework

Secondly it reduces the supply chain complexity given the supplies of only wire and powders. Thirdly it reduces the time and the cost of the support service with a related reduction of total cost of ownership. Finally, providing flexible manufacturing capability to a defensive platform in a battlefield featured with disrupted supply chain may improve its ability to recover capability and improve its survivability and lethality.

- *Phase 1 – "Define Mission":* outlines the foundation of the assessment of AM applications in DS2. This phase answers key questions such as what type of mission will the platform perform? What is its target? What is the duration? For how long will the platform operate in OpEnv 2.2.1 "battle theatre"? What threats will it encounter?
- *Phase 2 – "Select Platform":* Royal Navy platforms have various platforms which differ dramatically in terms of their requirements and types of systems installed. It defines rules and limits for the RAS2 and identifies the system.
- *Phase 3 – "Select" SySco" and "OpEnv"":* as outlined in section 4.2 "Systems Configurations" (SysCo), DS2 have extended possible alternatives, moreover in case of Next Generation DS2 (AM based DS2) these alternatives or options increase due to the delocalisation of manufacturing (RAS2) In-port, In-DS2, In-supplier, In-Support vessel and In-platform. Phase 3 is the one featured with the most interesting "what-if scenarios" and extensive simulation to compare different options of Next generation DS2 will be carried out here.
- *Phase 4 – "Define critical-to-availability"* list: this phase consists in analysing and classifying functional components of the systems to be supported and outline which one are critical. The input of this phase is represented by a "System breakdown Structure" (SBS) which is a document provided by the "Original Equipment Manufacturer" (OEM) of the system.
- *Phase 5 – "Select Technology":* this phase is used to select different technologies (SLM, WAAM and FDM) to process the geometry. Technologies have different performance envelope and capabilities.
- *Phase 6 – "Design for AM":* once the components have been identified and technology has been selected, the geometry must be processed to outline the feasibility, building strategy and KPI such as cycle time and deposition cost.

➢ *Phase 7 – "Manufacturing configuration":* this phase outline what processes are required to achieve the required quality standard and perform a qualification of the component. This is highly dependent on the material finishing required.

➢ *Phase 8 – "Dynamic simulation":* Given 1) high degree of complexity involved, 2) the need to partially represent the dynamics and relations of the real world and 3) the requirement to carry out experimentations, the framework must be translated into a Dynamic Model to carry out simulations and test what-if scenarios. The KPI's which need to be controlled are impact on Availability, cost of delivering the service and logistic delay time.

6.2.1 Transition to Additive Manufacturing opportunities

A critical part of the Framework is related with the transition from traditional manufacturing to AM production. Once the components are identified, the geometries need to be processed in CAD to understand how the AM technology can print this component.

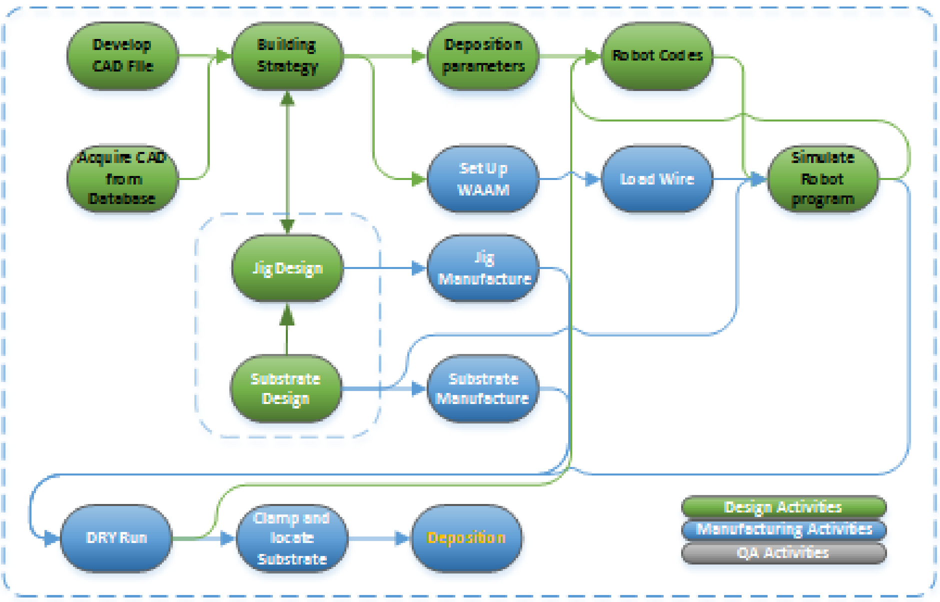


Figure 46 - Design Process Map

Moreover, this phase will outline the product cost and the time of deposition and compare it with the traditional way of producing it. In Figure 46 - Design Process Map outlines all the necessary "design activities" required to translate a 3D CAD file into an executable robot program for the actual deposition. Furthermore, as the components have been designed for traditional manufacturing, there might be a possibility to manipulate the geometry of the component for improved efficiency, lightweight or robustness. This is given mainly by the ability of AM for design freedom and complexity Busachi, Erkoyuncu, & Colegrove, (2015). To shift from traditional manufacturing to an AM environment the following must be carried out to define an end-to-end AM manufacturing system.

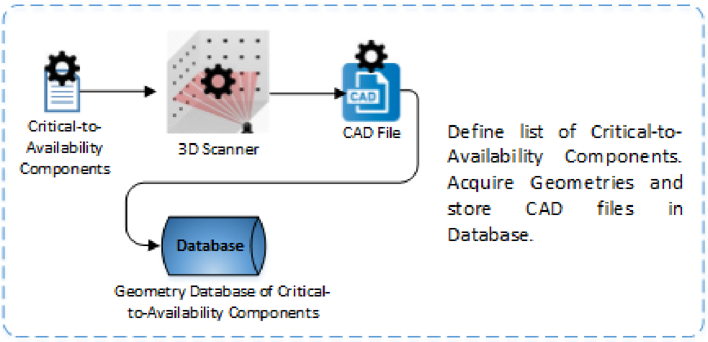


Figure 47 - Geometries database

Once the "Critical-to-Availability" list of components has been identified a database containing all the CAD files must be developed. If a CAD file is not available, the geometry must be acquired with a 3D scanner as outlined in Figure 47.

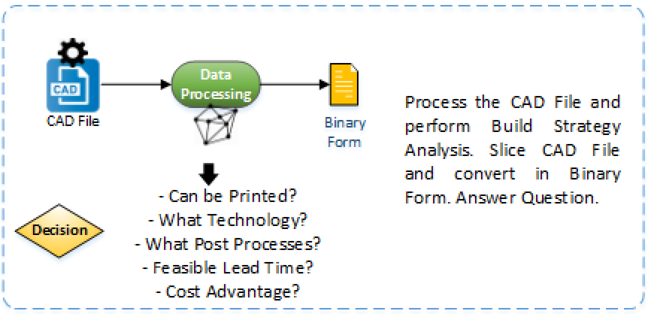


Figure 48 - AM assessment

The following step is to process the CAD file and define the building strategy. This will allow an estimation of time for the deposition and product cost through equations and answering critical questions related with the feasibility.

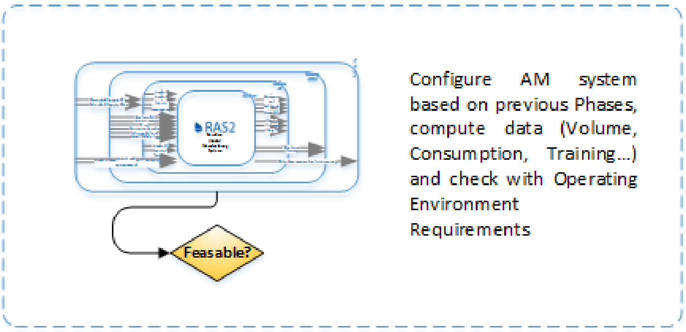


Figure 49 - AM system configuration

Finally, the end-to-end AM manufacturing system must be defined outlining its post-processes, raw material requirements, its space requirement and utility consumptions which must be assessed against the platform's OpEnv requirements.

6.3 Next Generation Support Services

A preliminary comparison between a Classic DS2 and a Next Generation DS2 outlines that the systems remain similar with the only exception that in a NG-DS2 there is a new element, E0, which represents the supplier of raw materials (wire or powder).

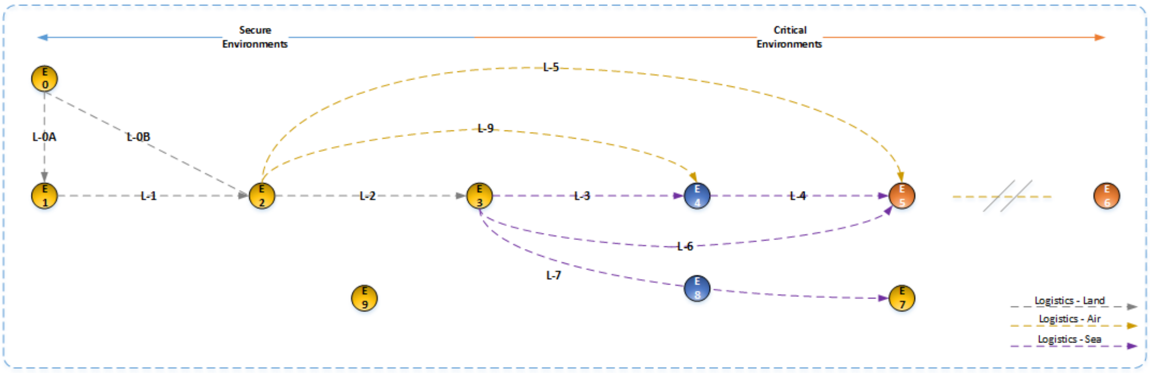


Figure 50 - Next generation DS2

E0 can supply both, E1 the supplier of components through L-0A and E2 the DS2 provider through L-A1, depending on the location of the RAS2. The system elements represent also the location options for the RAS2 as follows: In-Supplier, In-DS2 provider, In-Port, In-Support vessel, In-Defence platform and In-Forward base. Furthermore, the "Administrative Delay Time" (ADT) and the "Procurement Delay Time" (PDT) are theoretically eliminated as the utilization of the RAS2 will be limitless and accessible at any given time by MoD operators. Prints will be recorded and charges occurs at fixed times during the year. The RAS2 will enable elimination of OEM's delivery time and its marginality from product cost. Due to delocalisation, the NG DS2 will be featured with two logistics, an inbound logistic to provide the RAS2 with the raw materials and an outbound logistic to deliver the component to the defence platform. If the RAS2 is located In-Platform, then the outbound logistic is eliminated.

$$A_o = \frac{\boldsymbol{O_t} + S_t}{O_t + S_t + PM_t + CM_t + \boldsymbol{LD_t}}$$

22)

Finally, the availability equation outlines the new equation through which Availability of systems supported by NG DS2 can be measured. The LDT will vary based on where the AM equipment is in the DS2 system. SysCos of NG DS2 are not presented but are in total 21.

7 Additive Manufacturing – Decision Support System

7.1 Introduction

To perform case studies, a Decision Support System (DSS) software tool has been developed. The Decision Support System (DSS) is a software prototype engineered for "Research & Development" (R&D) units employed in early stages of "Capability Acquisition" (CA) programs. The targeted capability which is investigated for acquisition is defined as follow:

" the capability to additively manufacture critical-to-availability components next/close to the point of use only when they are required, to maximise Operational Availability and reduce cost and time of Defence Support Services (DS2)".

The software tool includes four novel mathematical models on Wire+Arc Additive Manufacturing (WAAM), Fused Deposition Modelling (FDM) and on the Supply Chain of a DS2. The DSS performs accurate and detailed product and service cost estimation and can simulate current and next-generation practices where AM is delocalised in various stages of the support system (i.e. a DS2 provider, a vessel, a port and a forward base).

The AM-DSS has been developed in Visual Basic programming language using a user friendly Interactive Design Environment (IDE) called Visual Studio. This programming platform has been selected given its versatility, flexibility and ability to develop standalone software tool applications. To develop the AM-DSS, the Conceptual Framework has been analysed and transformed into an algorithm that governs the AM-DSS, Inputs and desired Outputs have been identified and a relevant AM-DSS Architecture has been developed. The AM-DSS Architecture outlines three main modules, Module – 1 represents the Logistic platforms, Module - 2 represents the Additive Manufacturing Cost & Time estimation and Module - 3 represents the simulation and estimation environment.

The Additive Manufacturing – Mathematical Models have been translated into executable codes in Visual Basic and allocated to Module-1 and Module-2. Module – 3, the simulation environments, has been coded using as reference the DS2 – SoI.

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.

The AM-DSS is made of three different modules as outlined in Figure - 51: 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.

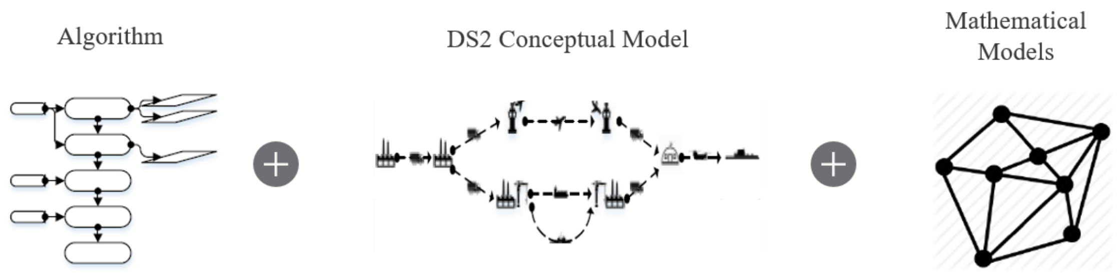


Figure 51 - AM-DSS Elements

The AM – DSS is comprised of four main elements outlined in Figure 51: 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. The module performs static and deterministic simulations but randomness can be easily modelled with pseudo-random generators. Given that Defense 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.

The architecture of the AM-DSS outlines how the modules are integrated and what are the inputs and outputs of each module.

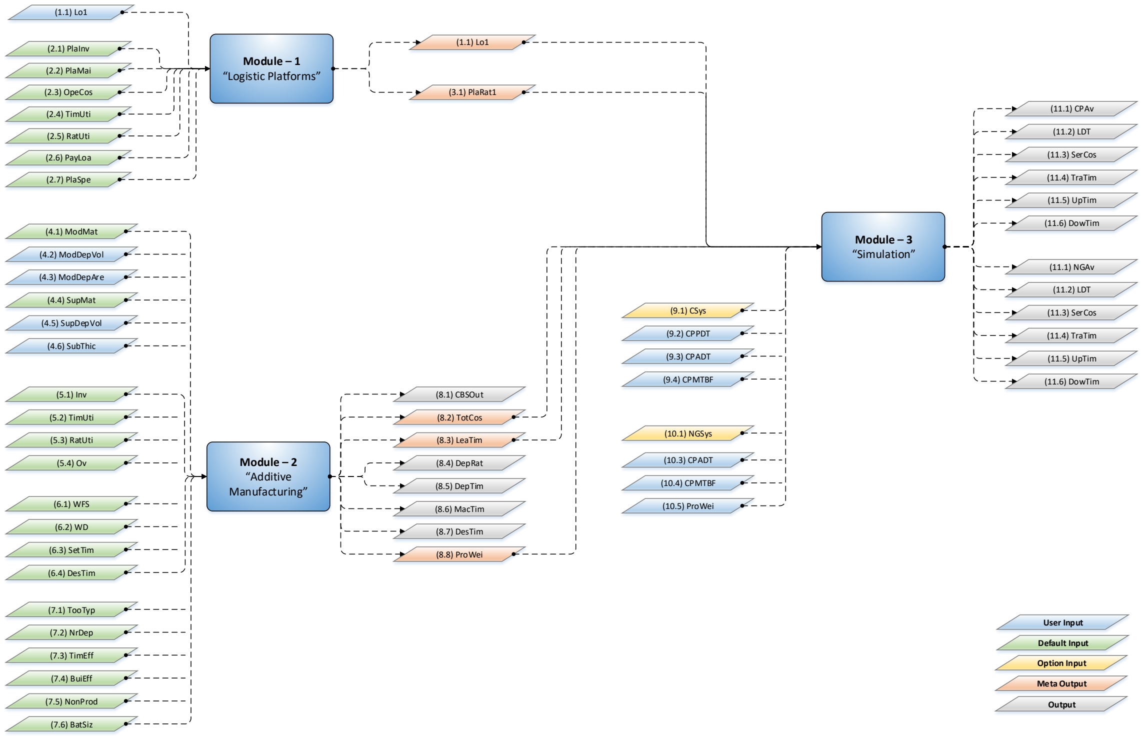


Figure 52 - AM-DSS Architecture

Module-1 requires the user to set the logistic distances between each system elements, the other inputs are set as default and refer to the logistic platforms. Module - 2 requires the user to input the material type of the product, its volume and the volume of its supports, the other inputs are set as default. Module – 3 requires the user to select the system configurations of both, current practices and next generation one and finally input the data related to availability. With these input the AM-DSS can provide accurate data on time and costs of both approaches allowing the user to compare the solutions. The outputs of the AM-DSS are the availability, the Logistic Delay Time (LDT), the Service Cost, the Travel Times, the Up Time and Down Time.

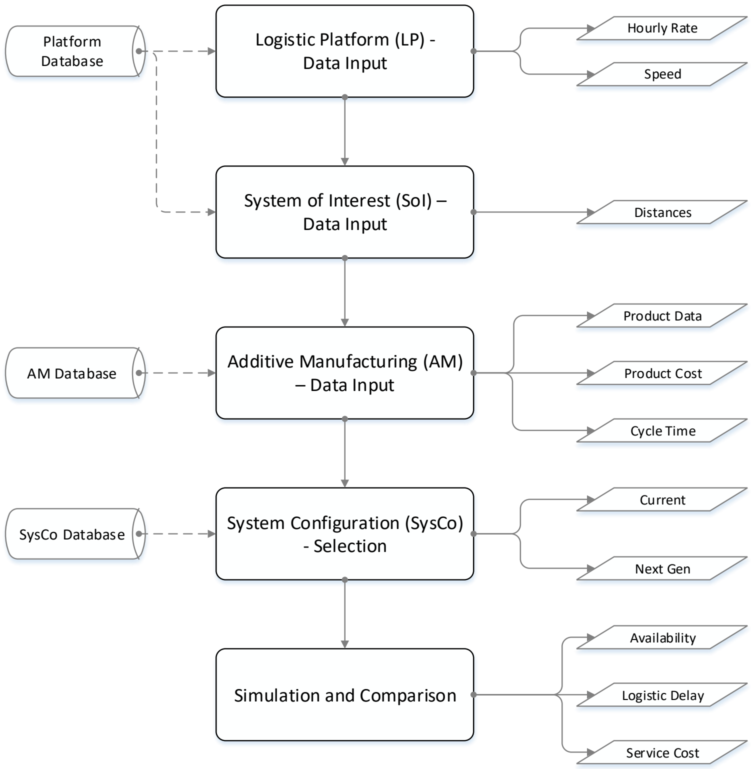


Figure 53 - Algorithm

The algorithm of the DSS is presented in Figure 53. It consists of five phases through which the user must go through to perform an exhaustive assessment of AM applications in DS2.

7.2 AM-DSS Modules

This section will explain the constituent modules of the AM-DSS software tool which is made of 3 integrated modules accessible through a menu.

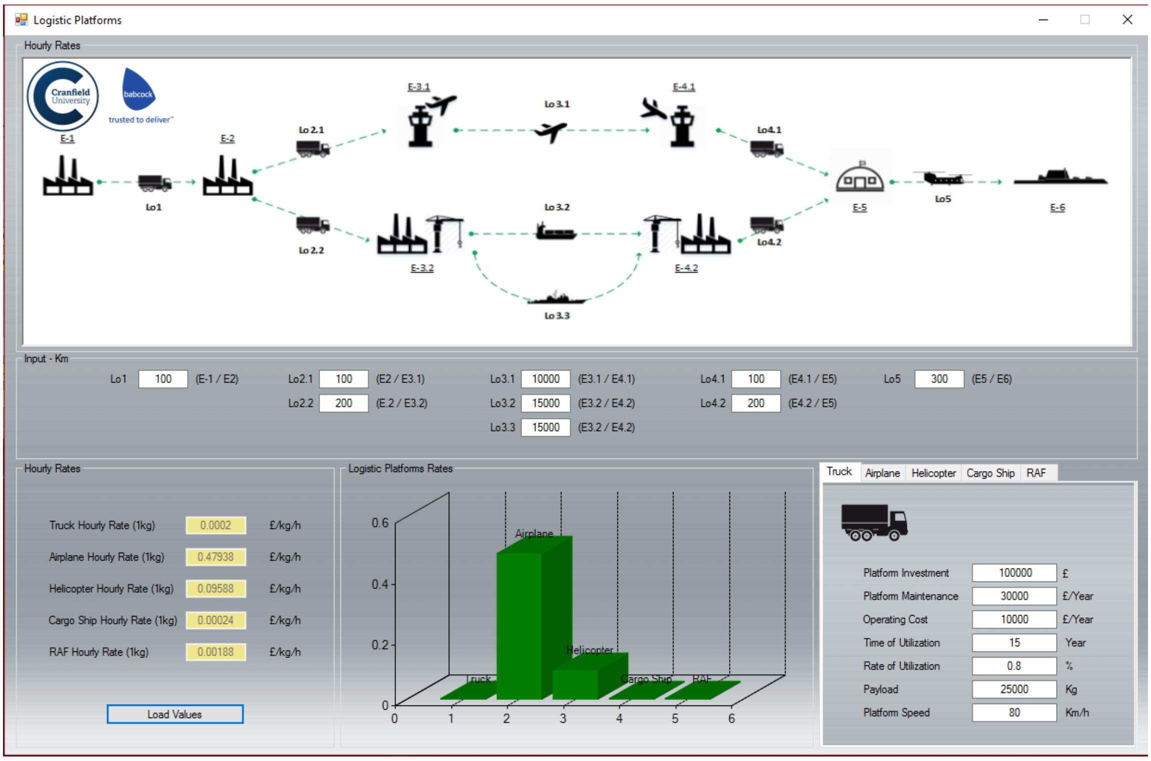


Figure 54 - Logistics

Phase 1 and 2 are embedded in Module - 1 which is outlined in Figure 54. Through this module the user must input the distances expressed as Km for each available logistic (Lo1 to Lo5). Moreover, the user needs to populate the model with the financial data on each logistic platform: platform investment (£), platform maintenance (£/year), operating cost (£/year), time of utilization (years), rate of utilization (%), payload (kg) and the average speed of the platform (km/hrs). The variables are fed into a mathematical equation which computes the hourly rate per kg for each platform. Once the variables have been loaded the module sends them as outputs to Module 3.

Module - 2 represents the mathematical model of the AM technology, in Figure 55 an example of Wire+Arc Additive Manufacturing (WAAM) which is largely considered the most promising solution for large structural components in the maritime context.

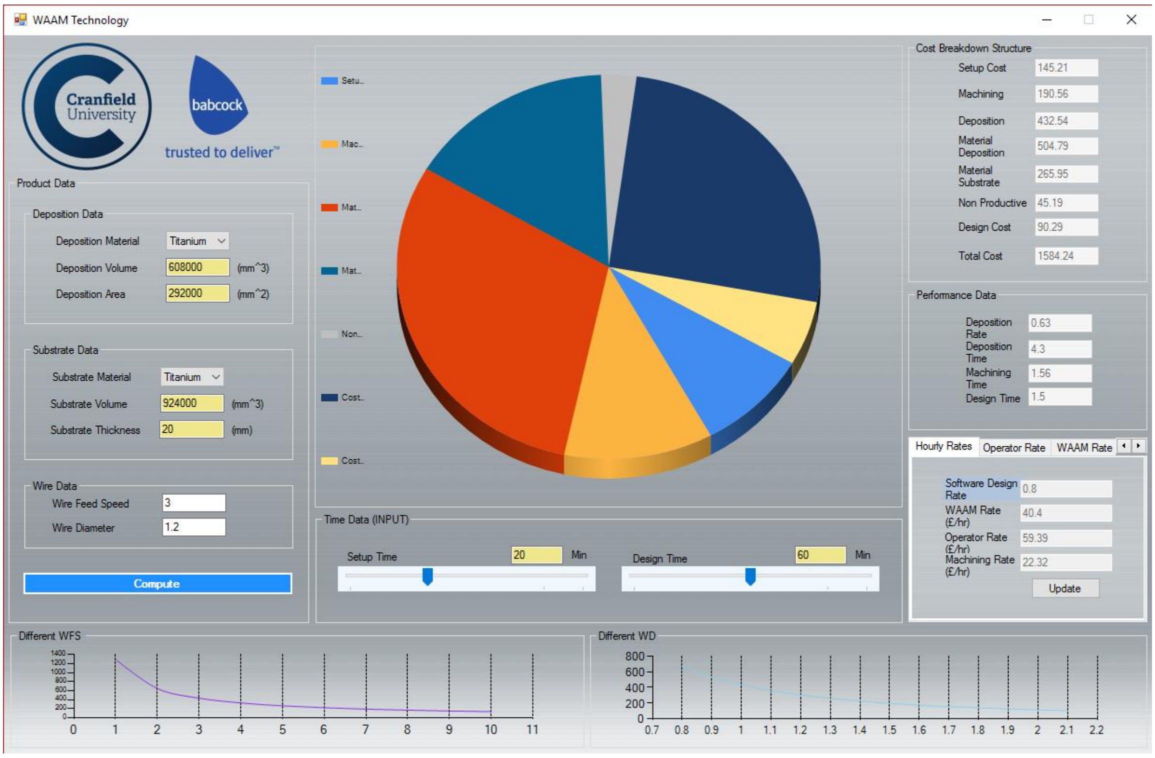


Figure 55 - Additive Manufacturing

The user needs to input the product data, type of material (Aluminium, Titanium, 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 variable of the process which have major impact on performance data. The module allows to include the setup time and design time which in some situation 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 7 cost elements and a set of performance data such as the cycle time, deposition rate and design time. Moreover, a small 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.

Module - 3 represents the simulation environment where the user can compare the current practices, where manufacturing occurs in the back-end of a DS2 and next generation practices where AM is delocalised in the front-end.

Figure 56 - Simulation

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, the PDT is eliminated and substitute with the Cycle Time of the AM system. Once the selection has been made, the DSS performs automatically the calculations and provide the user with the following key performance indicators as outputs: Availability, Travel Times, Service Cost.

7.3 Defence Support Services (DS2) - Conceptual Model

A DS2 provider aims to support complex engineering systems installed on defensive platforms. In the case of the Royal Navy, these platforms are aircraft carriers, destroyers, frigates and submarines. The Royal Navy platforms 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.

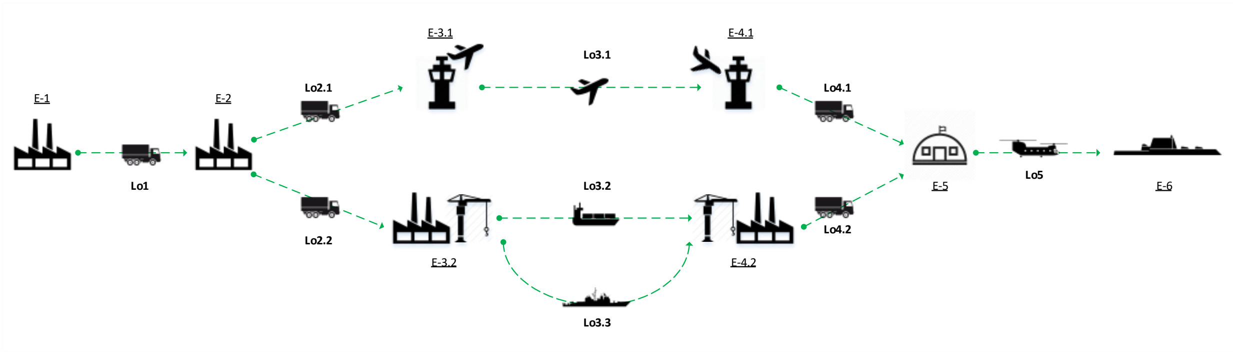


Figure 57 - DS2 Conceptual Model

The Conceptual Model of a DS2 is outlined in Figure 57 and is composed of the following elements:

Tag	Icon	Name
E-1		Supplier
E-2		DS2 Provider
E-3.1		Outbound Airport
E-3.2		Outbound Port
E-4.1		Inbound Airport
E-4.2		Inbound Port
E-5		Forward Base
E-6		Defence Platform

Figure 58 - DS2 System Elements

The Systems Elements are interconnected through the logistic links, which are of three different types: 1) Land, 2) Sea and 3) Air.

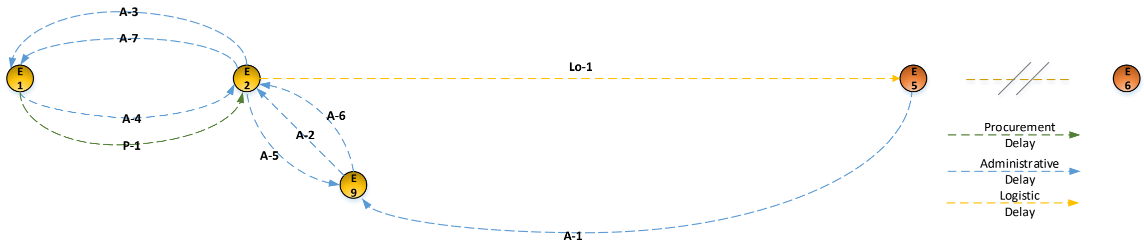


Figure 59 - DS2 Dynamics

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, Availability. Availability is a measure of uptime over total-time (uptime + downtime) and measures the predicted ability of a complex system to achieve its purpose when required to do so.

As previously described, a DS2 system's elements need to interact with each other to deliver value to Royal Navy. This interaction is given by three links: 1) logistics (L°), 2) Administrative delay (A°) and 3) Procurement delay (P°). These links are therefore critical variables of an expanded equation of Availability. A DS2 provider wants to minimise these values to maximise Availability.

Given the use of deployable and active platforms, which may operate remotely in the world, the major factor which negatively influences Availability is given by the logistic delay time (LDT), and its relation with distance and speed of delivery.

A DS2 has different System Configurations (SysCo) through which it can deliver value to the Royal Navy.

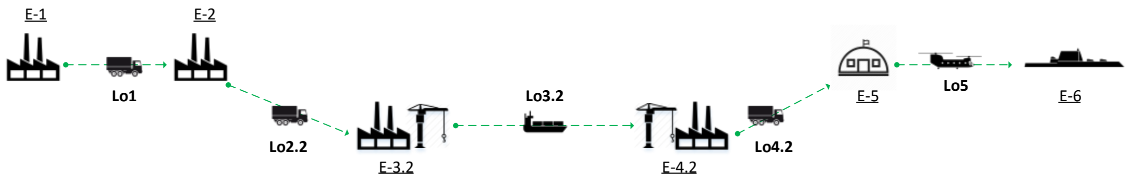


Figure 60 - CP-SysCo-2

In current practices, manufacturing occurs in the back-end of the DS2 as outline in Figure 60.

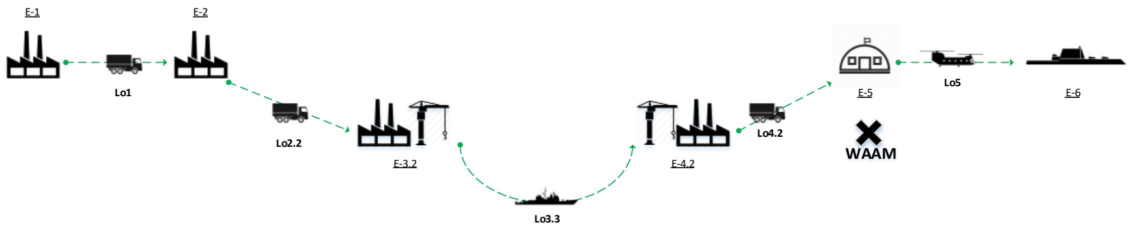


Figure 61 - NG-SysCo-4.1

In next generation practices, manufacturing can be delocalised in the front-end till the forward base, as outlined in Figure 61.

	TAG	Location of Manufacturing	Sequence
Current Practices	CP-SysCo-1	**E-1**	Lo1/Lo2.1/Lo3.1/Lo4.1/Lo5
	CP-SysCo-2	**E-2**	Lo1/Lo2.2/Lo3.2/Lo4.2/Lo5
	CP-SysCo-3	**E-3**	Lo1/Lo2.2/Lo3.3/Lo4.2/Lo5
Next Generation Practices	NG-SysCo-1.1	**E-2**	Lo2.1/Lo3.1/Lo4.1/Lo5
	NG-SysCo-1.2	**E-2**	Lo2.2/Lo3.2/Lo4.2/Lo5
	NG-SysCo-1.3	**E-2**	Lo2.2/Lo3.3/Lo4.2/Lo5
	NG-SysCo-2.1	**E-3.2**	Lo3.2/Lo4.2/Lo5
	NG-SysCo-2.2	**E-3.2**	Lo3.3/Lo4.2/Lo5
	NG-SysCo-3.1	**Lo3.3**	Lo4.2/Lo5
	NG-SysCo-4.1	**E5**	Lo5

Figure 62 - System Configurations

This section outlines the Inputs and Outputs of each module and categorise them into “User Input” where the user must set some values, “Default Input” where the values are already provided, “Meta Output” which is manipulated data which is pseudo significant, "Option Input" where the user must choose between a limited number of option available and "Output" which is the result of the model and is significant to the user.

	Tag	Code	Description	Value Type	Unit
Logistic Distances	1.1	Lo1	Distance from E-1 to E2	User Input	Km
	1.2	Lo21	Distance from E-2 to E3.1	User Input	Km
	1.3	Lo22	Distance from E-2 to E3.2	User Input	Km
	1.4	Lo31	Distance from E-3.1 to.41	User Input	Km
	1.5	Lo32	Distance from E-3.2 to 4.2	User Input	Km
	1.6	Lo33	Distance from E-3.2 to E4.2	User Input	Km
	1.7	Lo41	Distance from E-4.1 to E5	User Input	Km
	1.8	Lo42	Distance from E-4.2 to E5	User Input	Km
	1.9	Lo5	Distance from E-5 to E6	User Input	Km
Logistic Platforms (N5)	2.1	PlaInv	Platform Investment	Default Input	£
	2.2	PlaMai	Platform Maintenance	Default Input	£/year
	2.3	OpeCos	Operating Cost	Default Input	£/year
	2.4	TimUti	Time of Utilisation	Default Input	years
	2.5	RatUti	Rate of Utilisation	Default Input	%
	2.6	PayLoa	Payload	Default Input	Kg
	2.7	PlaSpe	Speed	Default Input	Km/h
Platform Rates	3.1	PlaRat1	Rate of Platform 1 (Truck)	Meta Output	£/kg/h
	3.2	PlaRat2	Rate of Platform 2 (Airplane)	Meta Output	£/kg/h
	3.3	PlaRat3	Rate of Platform 3 (Helicopter)	Meta Output	£/kg/h
	3.4	PlaRat4	Rate of Platform 4 (Cargo)	Meta Output	£/kg/h
	3.5	PlaRat5	Rate of Platform 5 (RAF)	Meta Output	£/kg/h

Table 9 – Module 1 Inputs/Meta Outputs

All the relevant Inputs and Meta Outputs of Module – 1 are outlined. These refer to the Logistic Platforms and Logistic Distances of the Defence Support Service (DS2).

In Table – 9 all the relevant User Inputs, Default Inputs, Option Inputs and Meta Outputs of Module - 2 are outlined. These refer to the Additive Manufacturing technology and Product.

	Tag	Code	Description	Value Type	Unit
Product Data	4.1	**ModMat**	Model Material	Option Input	Type
	4.2	**ModDepVol**	Model Deposition Volume	User Input	Mm3
	4.3	**ModDepAre**	Model Deposition Area	User Input	Mm2
	4.4	**SupMat**	Support Material	Option Input	Type
	4.5	**SupDepVol**	Support Deposition Volume	User Input	Mm3
	4.6	**SubThic**	Substrate Thickness	User Input	mm
Resources Rates	5.1	Inv	Investment	Default Input	£
	5.2	TimUti	Time of Utilisation	Default Input	Years
	5.3	RatUti	Rate of Utilisation	Default Input	%
	5.4	Ov	Overheads	Default Input	%
Process Data	6.1	WFS	Wire Feed Speed	Default Input	Mm/sec
	6.2	WD	Wire Diameter	Default Input	Mm
	6.3	SetTim	Setup Time	Default Input	Min
	6.4	DesTim	Design Time	Default Input	Min
Operations Data	7.1	TooTyp	Tool Type	Option Input	Type
	7.2	NrDep	Nr of Depositions	Default Input	Nr
	7.3	TimEff	Time Efficiency	Default Input	%
	7.4	BuiEff	Build Efficiency	Default Input	%
	7.5	NonProd	Non-Productive Time	Default Input	Min
	7.6	BatSiz	Batch Size	Default Input	Nr
WAAM Data	8.1	CBSOut	Cost Breakdown Structure	Meta Output	£
	8.2	TotCos	Total Cost	Meta Output	£
	8.3	LeaTim	Lead Time	Meta Output	Hrs
	8.4	DepRat	Deposition Rate	Meta Output	Kg/Hrs
	8.5	DepTim	Deposition Time	Meta Output	Hrs
	8.6	MacTim	Machining Time	Meta Output	Hrs
	8.7	DesTim	Design Time	Meta Output	Hrs
	8.8	ProWei	Product Weight	Meta Output	Kg

Table 10 - Module 2 Inputs/Meta Outputs

In Table – 10 all relevant Option Inputs, User Inputs, Meta Outputs of Module – 3 are outlined. These refer to the Defence Support Service configurations and to the Product's reliability data.

	Tag	Code	Description	Value Type	Unit
Current Practices	9.1	CPSys	CP System Configuration	Option Input	Sequence
	9.2	CPPDT	Procurement Delay Time	User Input	Hrs
	9.3	CPADT	Administrative Delay Time	User Input	Hrs
	9.4	CPMTBF	Mean Time Between Failures	User Input	Hrs
	9.5	ProWei	Product Weight	Meta Output	Kg
Next Generation Data	10.1	NGSys	NG System Configuration	Option Input	Sequence
	10.2	WAAMCT	WAAM CT	Meta Output	Hrs
	10.3	CPADT	Administrative Delay Time	User Input	Hrs
	10.4	CPMTBF	Mean Time Between Failures	User Input	Hrs
	10.5	ProWei	Product Weight	Meta Output	Kg

Table 11 - Module 3 Inputs / Meta Outputs

In Table – 11 all the DSS's outputs have been outlined. These refer to the Key Performance Indicators (KPIs) of a Defence Support Service.

Table 12 - DSS Outputs and Results

	Tag	Code	Description	Value Type	Unit
Current Practices Data	11.1	CPAv	CP Availability	Output	%
	11.2	LDT	Logistic Delay Time (LDT)	Output	Hrs
	11.3	SerCos	Service Cost	Output	£
	11.4	TraTim	Travel Time	Output	Hrs
	11.5	UpTim	Up Time	Output	Hrs
	11.6	DowTim	Down Time	Output	Hrs
Next Generation Data	12.1	NGAv	NG Availability	Output	%
	12.2	LDT	Logistic Delay Time (LDT)	Output	Hrs
	12.3	SerCos	Service Cost	Output	£
	12.4	TraTim	Travel Time	Output	Hrs
	12.5	UpTim	Up Time	Output	Hrs
	12.6	DowTim	Down Time	Output	Hrs

A total of 50 Inputs are required to perform the simulation.

8 Verification & Validation

8.1 Validation on development process

To obtain reliable information, data and expertise for validation, key experts of the UK Defence Value Chain have been involved. As follows the list of experts and the reference section outlines where these experts have been involved in both development and validation for Additive Manufacturing (AM), System of Interest (SoI), Conceptual Framework (CF), Current Practices (CP), and Mathematical Models (MM).

Organisation	Type	Years of Experience	Position	Reference
"Ministry of Defence" (MoD)	Royal Navy	15	NAVY Eng Spt-Sup SoI 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

Table 13 - List of Experts

The elicitation process has been carried out in two forms. The first form involved 6 workshops which lasted from 3 to 5 hours in which participants went through an individual session where they had to “think on their feet” and following a group session where collective brainstorming has been carried out. The second form involved individual interview with the support of structured charts with a related guide where experts carried out the activity individually.

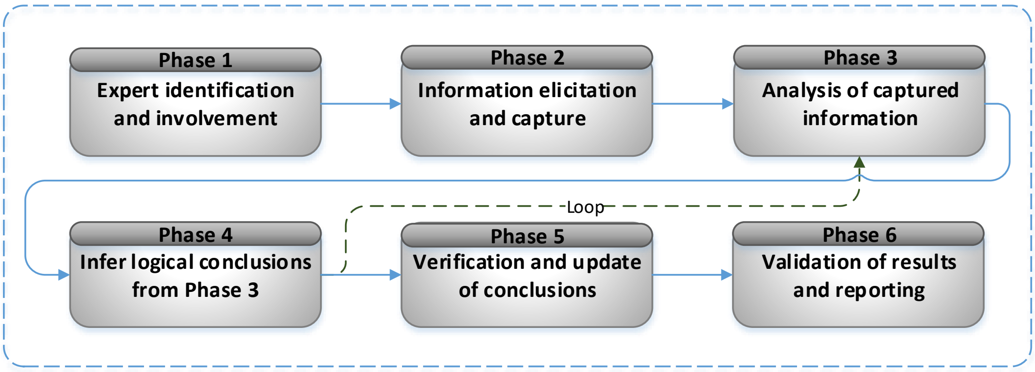


Figure 63 - Elicitation Process

The research approach adopted to capture the expertise and develop conclusions is outlined in Figure 63. The elicitation process is made of 6 phases:

- Phase 1: organisations of the UK Value Chain have been contacted and requested to nominate an experienced and reliable source of expertise.
- Phase 2: the information elicitation process has been carried out through an induction of the activity aim and using structured charts, moreover the audio of the sessions has been recorded. (MoD – 2 hours, 14 people / DS2 – 2 hours, 6 people)
- Phase 3: once the information has been captured the results have been analysed and reorganised.

- Phase 4: once the information has been reorganised it has been displayed on an A3 chart with references which allowed the author to have an exhaustive understanding of the overall inputs received.

- Phase 5: the draft has been sent to the experts for verification and where necessary experts made recommendations on how to improve it.

- Phase 6: the results have been validated and reported.

This approach has been adopted to develop, verify and validate the "System of Interest" (SoI), the Conceptual Framework, the Mathematical Models.

Table 14 – Conceptual Framework validation

Framework features	Strongly Disagree	Disagree	Fair	Agree	Strongly Agree
Significant, original and novel			X	X, X, X, X, X	X, X
Well structured				X, X, X, X	X, X, X, X
Logic				X, X, X, X	X, X, X, X
Fit for purpose			X	X, X, X	X, X, X, X
Accurate/detailed enough			X, X	X, X	X, X, X, X

- Is the System of Interest exhaustive? Does it include the most significant elements?

- **Table 15 - System of Interest validation**

Reference	Very Incomplete	Incomplete	Fair	Exhaustive	Very Exhaustive
1			X	X, X, X, X, X	X

- Are the cost estimates accurate enough? (Mathematical Models)

- **Table 16 – Mathematical Model validation**

Reference	Very Inaccurate	Inaccurate	Fair	Accurate	Very Accurate
1			X, X	X, X, X, X	X

As follows a comment provided on the Additive Manufacturing Mathematical Models:

"The process generally looks comprehensive. My only suggestions are (note that we use our FDM machine for in-house research jobs so our process might be different to that of a bureau): In the Geometric Properties section, we would usually consider the process parameters (layer thickness, type of supports, type of fill) in parallel with defining the build orientation and supports to get the best results. In you process the process parameters are set after the build orientation and supports have been defined and there is no feedback loop after setting the process parameters I would have included a feedback loop from the «Compute Volume and Time» task back to the build orientation. We often iterate the process parameters and build orientation if the volume or time are too high."

This section outlines the validation activity of the AM-DSS which includes the mathematical models, the conceptual framework and the System of Interest previously described in each chapter. As follow the list of the experts involved in the validation activity of the AM-DSS.

Table 17 - List of Experts

Tag	Position	Experience	Organisation
1	**Technology Acquisition Lead**	8 years	Support Service provider
2	**Business Development**	25 years	Support Service provider
3	**Director of Engineering**	25 years	Support Service provider
4	**Head of Bids**	22 years	Support Service provider
5	**Director of Support**	40 years	Support Service provider
6	**Head of Capability**	30 years	Support Service provider
7	**Captain RN**	Lots	The Royal Navy
8	**Innovation Program Manager**	14	The Royal Navy
9	**Engineering Officer**	17	The Royal Navy
10	**Mechanical Engineer**	1	MoD's Contractor
11	**Thermal Analysis Specialist**	30	MoD's Contractor
12	**Systems Engineer**	35	MoD's Contractor
13	**Future Concepts**	9	MoD's Contractor
14	**Materials Engineer**	16	MoD's Contractor

1. Is the supply chain module exhaustive? Does it include the most important activities occurring within a Defence Support Service?

Strongly Disagree	Disagree	Fair	Agree	Strongly Agree
		3,6	1,2,4,7,8,9,10,11,12,13,14	5

2. Is the Cost Model exhaustive? Does it include the most important costs occurring within an Additive Manufacturing deposition?

Strongly Disagree	Disagree	Fair	Agree	Strongly Agree
		3,6	1,2,4,7,8,10,11,12,13,14	5,9

3. Is the Simulation exhaustive? Does it include the most important Key Performance Indicators of a Defence Support Service?

Strongly Disagree	Disagree	Fair	Agree	Strongly Agree
		3,6,8,11	1,2,4,7,10,12,13,14	5

As follow the list of suggested improvements:

- *Should include manpower, shortages, the Availability equation is a rather simple as in military context it will include more considerations. Failure rates of AM systems are missing as well as the qualification issues. P.S. the software tool has great utility (Royal Navy Captain).*

- *Should include waiting time between system elements also scrap rate should be considered, financial investment for setting up an AM defence support service system is missing (Innovation Program Manager – MoD's Contractor).*

- *Contracting time should be modelled as this may delay the support to CES which are out of support. Maritime Intra Theatre lift (MITL) should be modelled. In-Theatre movements of material should be considered (Engineering Officer – Royal Navy).*

- *Cost of transportation for wire and powder should be considered in the next-generation solution. Material library should be extended to larger set. Post-*

processing should be modelled for AM (Thermal Analysis Specialist – MoD's Contractor).

- *Should include delay time for loading and unloading, maintenance of AM machine should be modelled especially for forward locations (Future Concepts – MoD's Contractor).*

- *Differentiation between final part and temporary replacement should be taken in consideration (Principal Material Engineer – MoD's Contractor).*

- *The Logistic Platform module's mathematical model is high level; it should be improved with the MoD's input. Material library should be more flexible and allow user to input the cost per kg of each material as this is featured with variability (Technology Acquisition Lead – DS2 provider).*

- *Focus of the AM-DSS should be on time saving and not cost saving Should consider the time to repair the equipment as this might be critical in some situations (Business Development Manager – DS2 provider).*

8.2 Validation through Case Studies

This section outlines 3 case studies carried out with the Additive Manufacturing – Decision Support System (AM-DSS) to assess the impact of Additive Manufacturing applications in forward deployments in a Defence Support Service system. Focus of the case studies is the “Highly Mechanised Weapon Handling System” (HMWHS) currently installed on the Queen Elizabeth class aircraft carrier. The HMWHS provides mechanical handling of munitions, connects magazine, hangar, preparation area and flight deck, it is an unmanned vehicle controlled from 1 remote location which increases dramatically the throughput of the carrier.

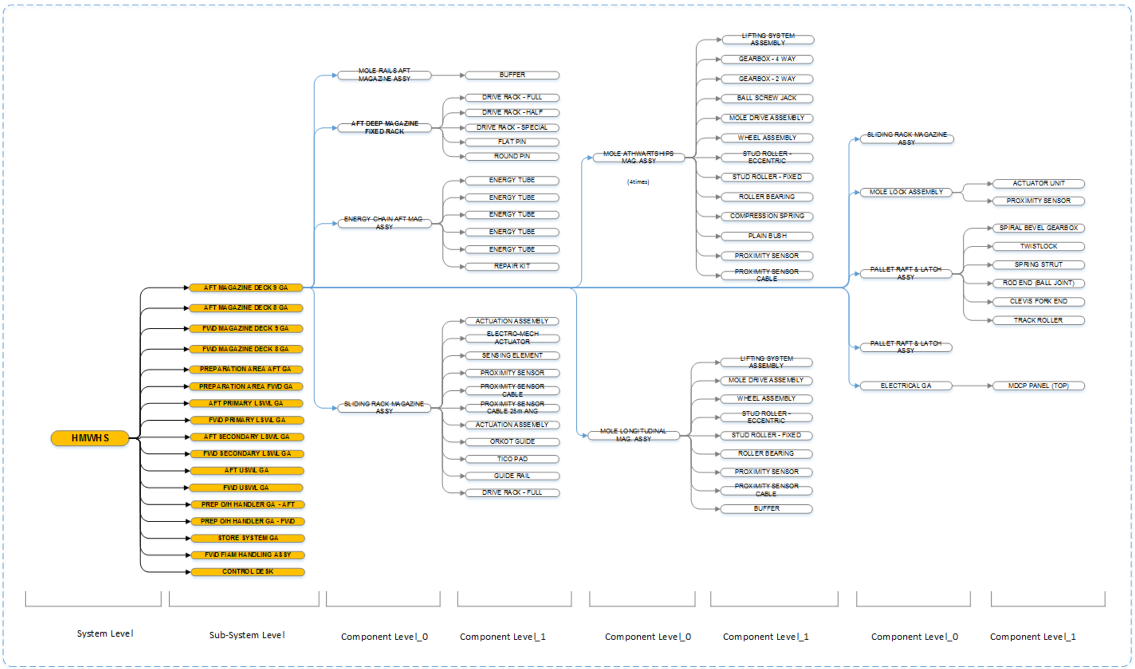


Figure 64 - System Breakdown Structure (SBS)

It is made of 17 Sub-Systems and each Sub-System is broken down further (up to 6 level) and is made of 1500 components. Each component has a Procurement Delay Time (PDT) of 2500 hours.

Name	Material	Dimension			Volume mm3	Volume cm3	Weight kg	MTBF
Component 1	STEEL	945	362.5	158	54,124,875.00	54,124.88	62	200000
Component 2	STEEL	408	315	250	32,130,000.00	32,130.00	86	100000
Component 3	STEEL	425	250	302	32,087,500.00	32,087.50	78	180000

Figure 65 - Product INPUTS

Three components have been selected and their data are outlined in Figure 65 - Product INPUTS, these are also the first set of inputs to the AM-DSS. The following set of inputs is related with the Logistic Platforms and are outlined in INPUTS given the inability to retrieve data from industry a web research has been carried out to retrieve representative data on platforms such as truck, airplane, helicopter, cargo ship and Royal Auxiliary Fleet (RAF).

Type	Truck	Airplane	Helicopter	Cargo Ship	RAF
Platform Investment	£ 100,000.00	£ 100,000,000.00	£30,000,000.00	£25,000,000.00	£20,000,000.00
Platform Maintenance	£ 30,000.00	£ 30,000,000.00	£ 9,000,000.00	£ 7,500,000.00	£ 6,000,000.00
Operating Cost	£ 10,000.00	£ 10,000,000.00	£ 3,000,000.00	£ 2,500,000.00	£ 2,000,000.00
Time of Utilization	15 years	30 years	30 years	40 years	40 years
Rate of Utilization	0.80%	0.90%	0.90%	0.90%	0.90%
Payload	25000 kg	10000 kg	15000 kg	5000000 kg	500000 kg
Platform Speed	80 km/h	900 km/h	300 km/h	20 km/h	33 km/h

Figure 66 - Logistic Platforms INPUTS

For the maintenance of each logistic platform it has been assumed a 30% of the Platform Investment and for the operating costs a 10% of the Platform Investment.

Logistic	Distance
Lo1	300 km
Lo2.1	200 km
Lo2.2	500 km
Lo3.1	5.500 km
Lo3.2	13.000 km
Lo3.3	13.000 km
Lo4.1	300 km
Lo4.2	400 km
Lo5	500 km

Figure 67 - Logistic Distances INPUTS

The third set of inputs is related with the distances between systems elements, and the location is omitted and fictional.

Description	Data
WAAM Investment	£ 181,000.00
Utilization Time	8000 hrs/year
Utilization Rate	0.80%
Overheads	0.30%
Machining Investment	£ 100,000.00
Utilization Time	8000 hrs/year
Utilization Rate	0.80%
Overheads	0.30%
Software Investment	£ 5,000.00
Utilization Time	5000 hrs/year
Utilization Rate	0.80%

Figure 68 - WAAM INPUTS

Last set of data input is related with the Wire + Arc Additive Manufacturing system and data has been obtained from the WAAMMat Experts.

8.2.1 Case Study - 1

Case Study 1 aims at comparing the current support service practices with the next generation one based on AM deployed at an outbound port. Component 1 is used for this case study.

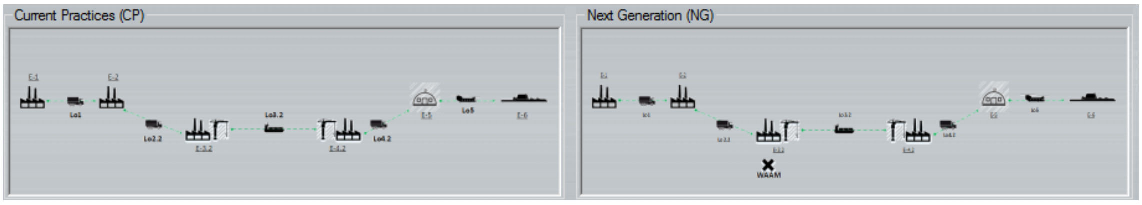


Figure 69 - System Configurations

In Figure 69 the system configurations are visualised and these are CP-SysCo-2 and NG-SysCo-2.1 which involves the use of a cargo ship.

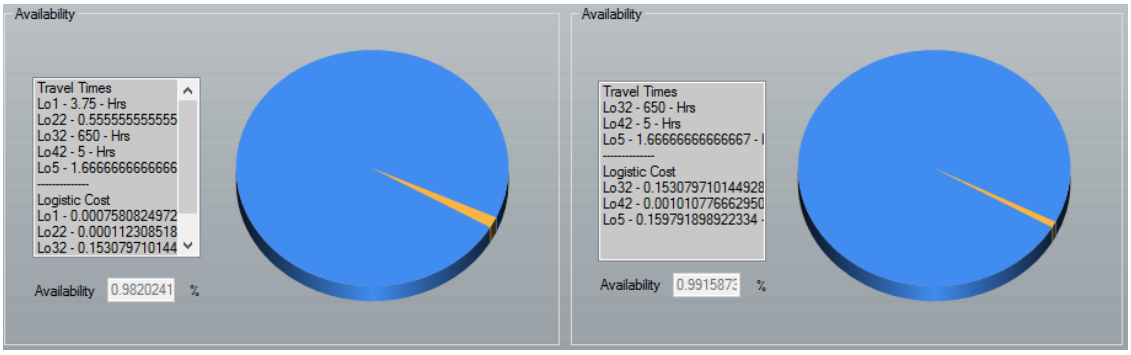


Figure 70 - Availability

The deployment of AM in the outbound port shows an improvement in the Availability of the system supported which increase from 98.20% to 99.16%.

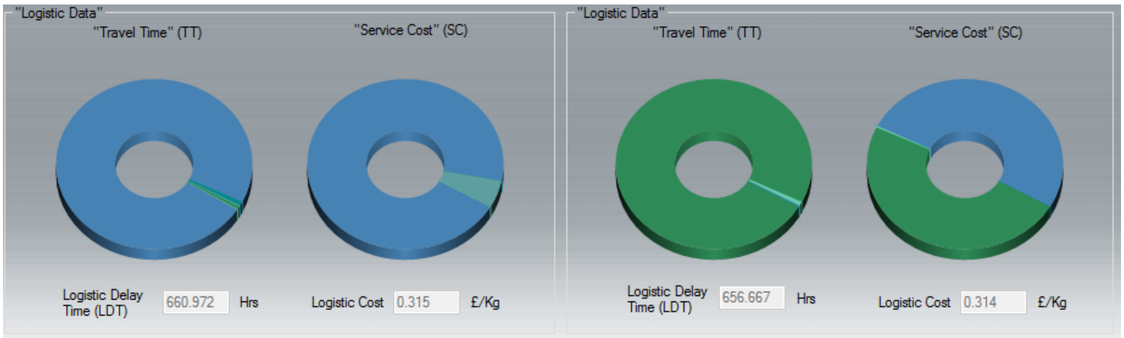


Figure 71 - Travel Time and Service Cost

The Logistic Delay Time reduced from 660.972 hours to 656.667 hours.

Finally, the product cost of Component – 1 printed with WAAM Technology is of £75,732 and requires 382 hours of deposition and 155 hours for machining the waviness, which leads to a Lead Time of 540 hours.

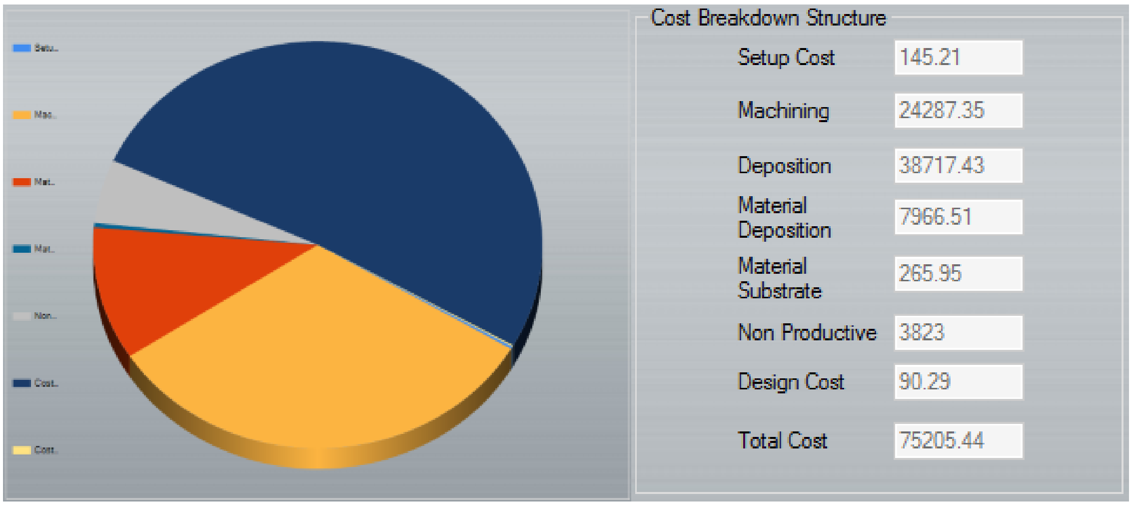


Figure 72 - Product Cost

The product cost is mainly made of the deposition cost which includes the rates of the WAAM system and the operators involved in supervising the deposition.

8.2.2 Case Study – 2

Case Study 2 aims at comparing the current support service practices with the next generation one based on AM deployed in a large Royal Auxiliary Fleet (RAF). Component 2 is used for this case study.

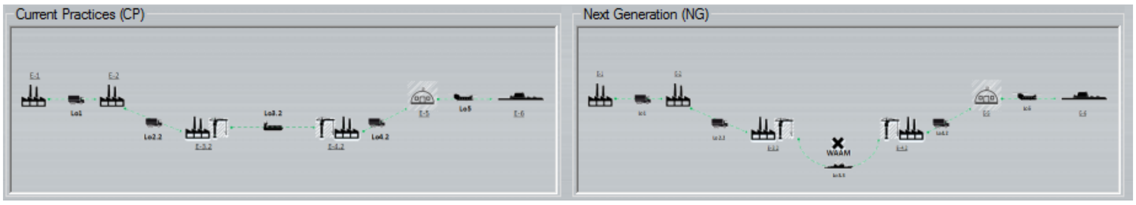


Figure 73 - System Configurations

In Figure 73 the system configurations are visualised and these are CP-SysCo-2 and NG-SysCo-3.1 which involves the use of a cargo ship in current practices and a Royal Auxiliary Fleet in next generation one.

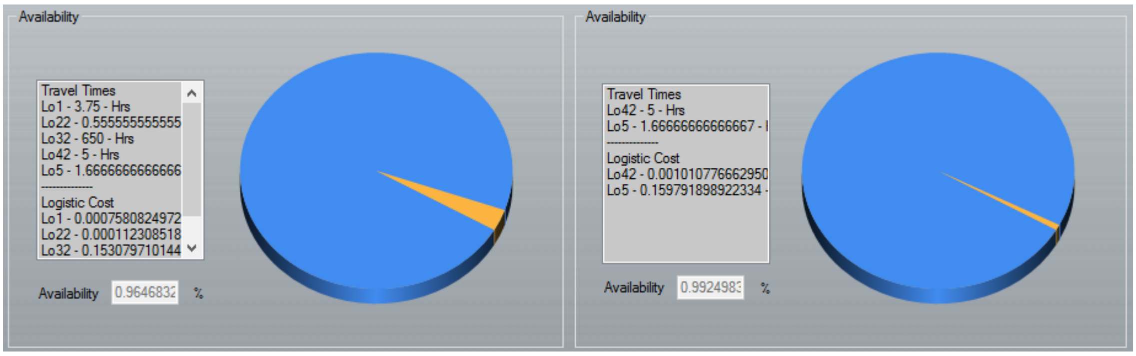


Figure 74 - Availability

The deployment of AM in the RAF shows an improvement in the availability of the system supported which increase from 96.47% to 99.25 %. This is a considerable result compare to case study-1.

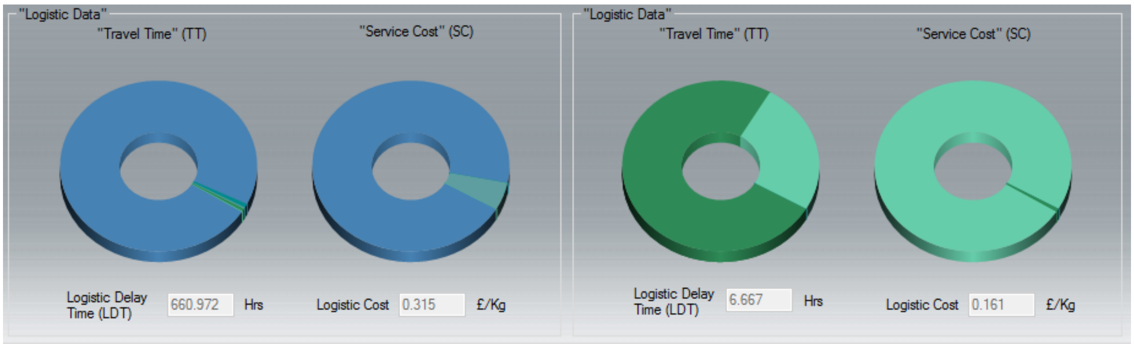


Figure 75 - Travel time & Service Cost

The Logistic Delay Time reduces from 660.97 hours to 6.67 hours given the deployment In-Theatre.

Finally, the product cost of Component – 2 printed with WAAM Technology is of £32,639 and requires 227 hours of deposition and 20 hours for machining the waviness which leads to a Lead Time of 247 hours.

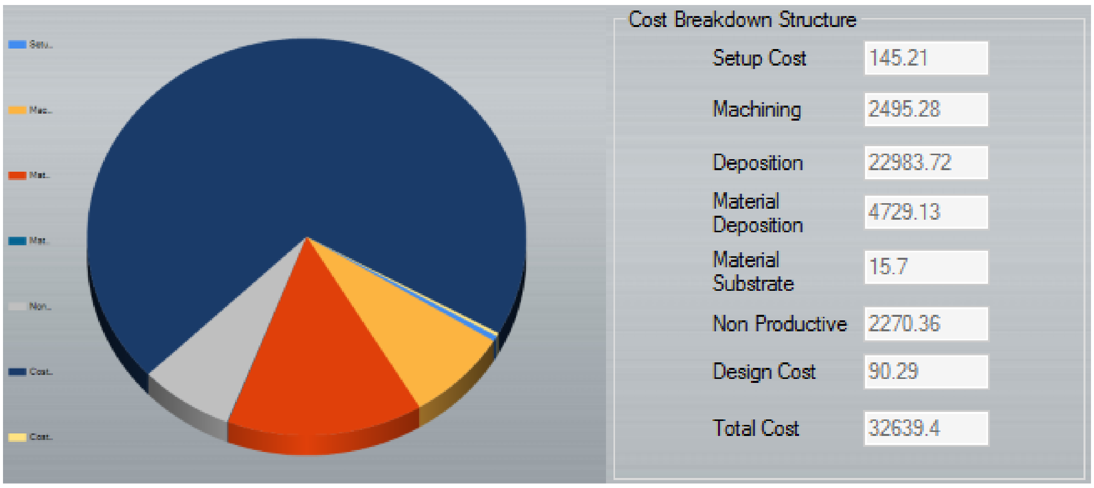


Figure 76 - Product Cost

The product cost is mainly made of the deposition cost, which includes the rates of the WAAM system and the operators involved in supervising the deposition.

8.2.3 Case Study – 3

Case Study 3 aims at comparing the current support service practices with the next generation one based on AM deployed in a Forward Base. Component 3 is used for this case study.

Figure 77 - System Configuration

In Figure 77 the system configurations are visualised and these are CP-SysCo-2 and NG-SysCo-4.1 which involves the use of a cargo ship in current practices and the deployment of AM in a Forward Base.

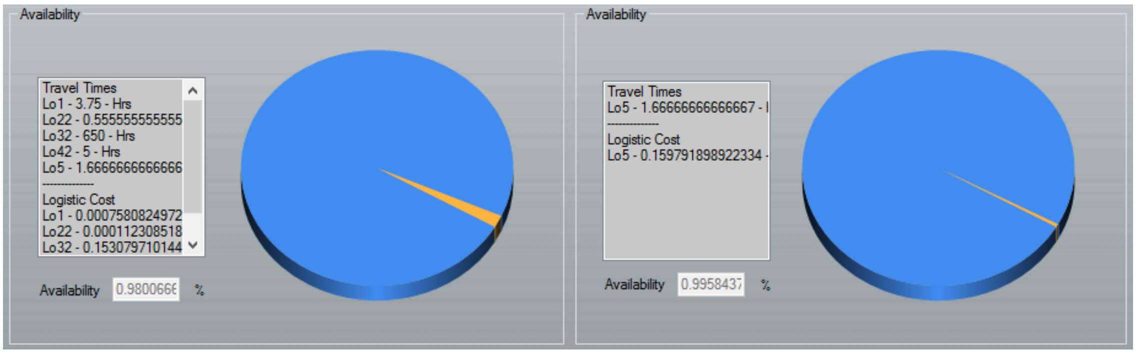


Figure 78 - Availability

The deployment of AM in a Forward Base shows an improvement in the Availability of the system supported which increase from 98.01% to 99.58%.

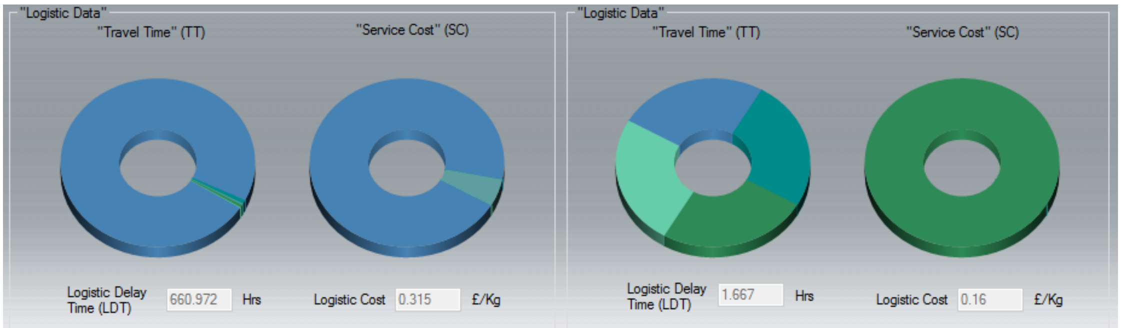


Figure 79 - Service Time & Service Cost

The Logistic Delay Time reduces from 660.97 hours to 1.67 hours.

8.3 Case Study Output

This section aimed at carrying out three case studies using three components of the Highly Mechanised Weapon Handling System (HMWHS).

Table 18 - Case Studies Summary

Case Study – 1			Case Study – 2			Case Study - 3		
Availability	98.20%	99.16%	**Availability**	96.47%	99.25%	**Availability**	98.01%	99.58%.
LDT	660.97	656.67	**LDT**	660.97	6.67	**LDT**	660.97	1.67
SysCo	SysCo-2	SysCo-2.1	**SysCo**	SysCo-2	SysCo-3.1	**SysCo**	SysCo-2	SysCo-4.1
UpTime	200,000	200,000	**UpTime**	100,000	100,000	**UpTime**	180,000	180,000
DownTime	3660	760	**DownTime**	3660	755	**DownTime**	3660	752

The aim of the case study is to simulate three scenarios of Additive Manufacturing deployments in the front-end of a defence support service system to provide spare parts to the HMWHS. Three simulations have been carried out, the first one simulated the deployment of AM in an Outbound Port, the second one the deployment of AM within a RAF, the last one simulated the deployment of AM in a Forward Base in Theatre. Below the results have been summarised.

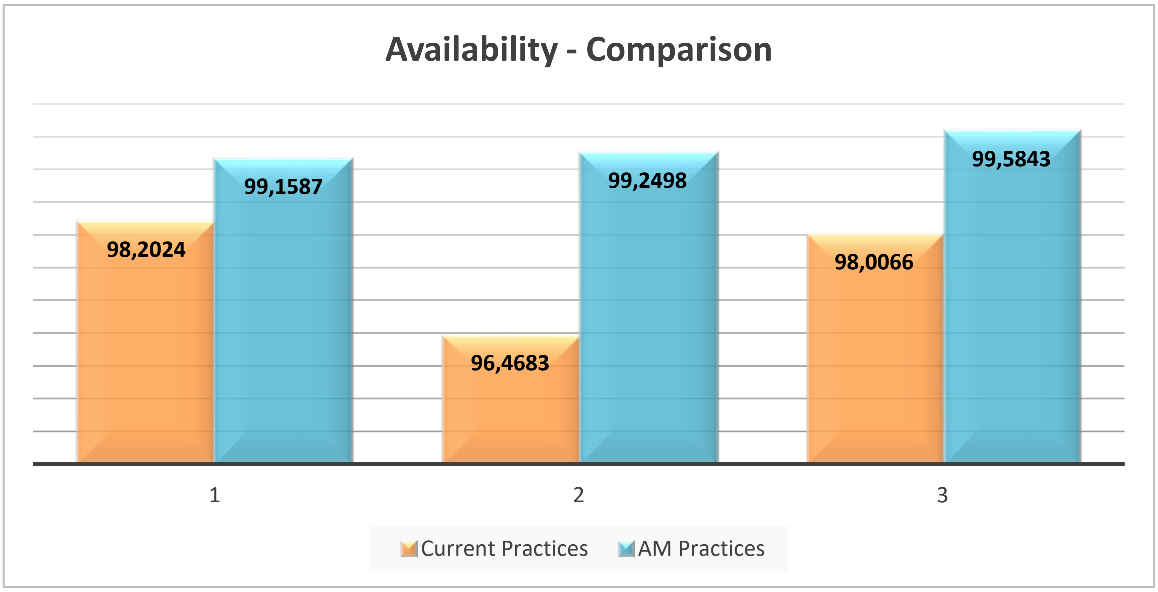


Figure 80 - Availability Comparison

Each simulation of deployed AM has been sided by the simulation of current practices. This has been carried out to perform a comparative study. The results show how AM can benefit defence support services through the reduction of the Logistic Delay Time and improvement of the availability of systems.

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 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.

9 Discussion, Conclusions and Future Work

This chapter will present the discussion dividing it in two subsections, one on Additive Manufacturing technology and one on the applications of the technology in the context of Defence Support Services. Following this, conclusions and future work are presented.

9.1 Additive Manufacturing

Wire based solutions are employed for larger components in which accuracy levels are not the most important factor. Martina, (2014) made a comparison of these two process methodologies for titanium applications. Powder based results are from a Selective Laser Melting machine while Wire Based results are from a "Wire+Arc Additive Manufacturing" machine.

Metals	Powder Based	Wire Based
Deposition Rate	0,2 Kg/h	3 Kg/h
Maximum size	35x30x20 cm3	Potentially no limit
Accuracy	25 micron	1-2 mm
Equipment Cost	>£300k	£200k
Material Cost	£500/kg of Powder	£150/kg of wire

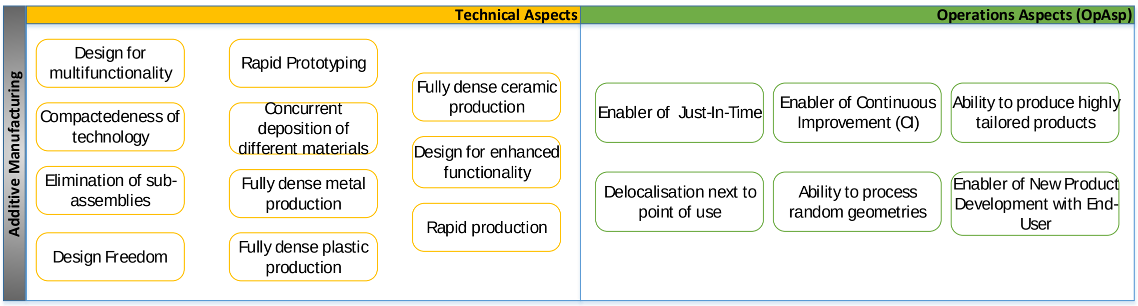
Figure 81 - Technologies comparison source: (Martina, 2015)

As it is outlined in Figure 81 the wire based solution has various advantages compared to the powder based solution. Lower investment cost, significantly higher deposition rates, lower costs of raw materials and no limits on build size make this solution particularly promising and attractive to industry. Secondary advantages are related with the elimination of preheating phases, no vacuum required and therefore lower elements vaporisation. Powder based solutions provide the user with enhanced design freedom. The accuracy level, up to 25 microns, gives the designer the possibility to access any kind of geometry. Higher accuracy level implies lower deposition rates which in some situations has a strong impact on lead times. This might represent a barrier of powder-based technologies. Deposition rates are influenced by energy density, scanning speed and layer thickness. Optimisation studies on these parameters are a focus study of Academia and Research Institutes to make these technologies more suitable for industrial applications. Moreover, from the literature it was possible to outline product cost structure of the two different processes and results showed that in PBF methodologies, the major contributor to cost is the rate of the machine due to high investment cost and slow deposition rates. In the case of WAAM process, the major contributor to the cost structure is material followed by the cost of welding.

To measure costs related with AM depositions, various techniques have been investigated. According to Ruffo & Hague, (2007) traditional cost modelling techniques have various disadvantages such as the inability to provide non-financial information which are critical to decision making. Moreover, they lack of accuracy providing high uncertainties in the estimate. Generally Intuitive techniques are subjective and results may vary dramatically based on experts interviewed. Furthermore, they are dependent on design features which in this case are not available. Analogical techniques are considered not fit for purpose as they depend heavily on data and in this case, historical data is not available as the system is still in design phase. To achieve higher accuracy, wide range of information and a realistic and detail allocation of overheads, an analytical technique has been selected, “Activity Based Costing” (ABC). The literature states that this is the main technique used for cost modelling of AM. The technique assigns manufacturing overheads to activities in a more logical manner tackling the problems related with high overhead distribution. In addition, ABC, does not require historical data as the model can be developed based on process maps and interviews with experts. As outlined the main benefits of ABC is the allocation of costs per where they are incurred improving accuracy and relevance. This allows detailing the cause of cost allowing the user to perform cost reduction analysis. To build the cost model, various documents must be developed to gather all the necessary information and data required. The most important document as reported by Zhai, (2012) is the process plan which outlines all the necessary manufacturing operations, the setup and unload activities and the post processes. This document organises the previous elements in a sequence and outlines the incurring times and resource consumptions. Another important document which needs to be developed is an IDEF0 map, as this provides details on inputs, output, controls and mechanism providing a more exhaustive approach to identify the sources of cost. To transform the data in cost, hourly rates of operators, machines and software must be calculated. This can be done in different ways moreover the allocation of overheads may vary dramatically based on organisation type and must be adapted on a case by case basis.

Through the literature review on AM, it was possible to define what are the opportunities provided by AM, these have been classified based on their nature and resulted in technical opportunities and operations opportunities. The classification has been carried out in the context of Defence Support Services for the Royal Navy.

Table 19 - AM Opportunities



AM (generic) technical benefits have been outlined such as design freedom, compactness of technology, physical supply chain complexity reduction, digital supply chain, delocalisation, concurrent deposition of different materials, ability to process metals, plastic, ceramics and electronics, re-design for enhanced functionality or efficiency, elimination of sub-assemblies, multi-functionality, mass customisation. These benefits are shared with different levels, amongst most of the available process methodologies such as Laser Cladding (LC), Wire + Arc Additive Manufacturing (WAAM), “Fused Deposition Modelling” (FDM), “Selective Laser Melting” (SLM). AM (generic) operation aspects have been outlined.

These AM operations aspects are based on “Manufacturing System Engineering”, “Lean Manufacturing” principles and “Lean Product and Process Development” and are possible due to the delocalisation of AM production next to the point of use and through the involvement of the end-user:

- AM as an enabler of “Continuous Improvement” in the work place: RN operators, while deployed carry out their daily activities (with standard tools, jigs, equipment and kits) through which they mature a direct experience. During this experience, they might develop/generate ideas to improve a process. If a platform has manufacturing capability based on AM they can convert ideas into functional products.

- AM is an enabler of Design Freedom; it can print rapidly any kind of geometry without the need to setup the machine or change tools: this aspect fits very well if we consider that AM is deployed in a platform to “serve” various “Complex Engineering Systems” (CES) made of an extended number of components which all differ one from another in terms of geometry. A sole AM machine can manufacture all the components when these will fail.

- AM as an enabler of improved Product Development: like the first point, AM allows to improve the Product Development. End-users, through the utilisation or direct experience develop/generate naturally ideas to improve their daily routine. AM as an enabler of CI is given by a combination of delocalisation of manufacturing next to the point of use, involvement of end-user (which detain the direct experience) in the PD and rapid prototyping capability to test the designs in the early stage.

- AM as an enabler of “Just-in-Time” (JIT): Considering the delocalisation of manufacturing within the platform, the “Logistic Delay Time” (LDT) is eliminated or dramatically reduced, moreover AM allows to achieve short CT of production. This combination allows to establish JIT principles which allows you to reduce the stocks of finished goods and produce only the components that you require and when you require them.

- AM as an enabler of mass customisation: AM allows you to produce highly tailored products to your needs and unique features. This aspect is fundamental when you require special tools to perform an operation, when you must produce a prosthesis tailored to the human body unique features or to provide special tools/small arms/body armours to tier-1 operators.

- AM as an enabler of improved Defence Support Services: through the delocalisation of AM within a platform, DS2 systems improve dramatically in terms of efficiency and cost.

9.2 Additive Manufacturing in Defence Support Services

The context of support services for Defence platforms involves the selling of the availability of one or more systems. The provider's profitability is dependent upon its ability to ensure high levels of availability over a long period (years). Traditionally this is made through the accumulation of components into warehouses within the platform. With a support service system based on AM, stocks of components can be reduced dramatically; this is due to the ability of the system to print the required component only when it is necessary. AM is particularly suitable for this application because it can process randomly any geometry without the need for adapting the manufacturing system to features of the component (no impact on setup activities). This aspect can cope with the randomness of failure rates of systems within the platform. As the components are printed in-platform, the lead time is reduced dramatically. Moreover, material efficiency and low Buy-to-Fly ratios of AM, leads to the conclusion that AM has a major advantage over subtractive manufacturing by providing better usage of materials. This aspect outlines the suitability of the technology for applications in Defence, Aerospace and Medical industry where advanced materials may reach high costs. Finally, the last part of the review outlined that the equation of availability might be improved in two different ways. An internal way is the optimisation of the reliability of the component and the reduction of time to maintain. An external way is the reduction of the delivery time, which is affected by the procurement delay, and the supply of the part. As AM is an enabler of delocalised and rapid manufacturing it is concluded that the technology can optimise availability of systems through the in-field production of the component on demand.

The review allowed the author to note that current AM cost models do not address consistently the challenges provided by the aleatory nature of support services. Defence Support Services are characterised by a stochastic operating environment and featured by uncertainty, variability and randomness, which needs to be modelled and added to the final model of the system. Examples of these features are human variability, failures of machines and quality failures, variance in cycle times, variance in the skills of the operators and finally fatigue effects on worker performance (Al-Zuheri et al., 2012).

Additive Manufacturing (generic) is a disruptive technology which benefits from design freedom, short manufacturing lead times, low buy-to-fly (BTF) ratios, complexity for free and requires limited space for operating. AM can be used for both, printing new components and repair broken ones (if combined with machining and 3D scanner). AM has the potential to reduce or eliminate sub-assemblies, access to new geometries and improve the performance of components. AM production aspects is Lean, it benefits from “pull” and “just-in-time” moreover the technology can process random geometries without any impact on setups. AM can be deployed for components, humanitarian aid, tools, repairs, temporary replacement, prosthesis, embedded sensors, drones and consumables.

As follow some findings on AM technologies:

- Powder bed technologies are more applicable to small complex geometries given their high accuracy levels.
- Blown powder technologies are highly suitable for repairs but also suitable for medium to low complex geometries.
- Wire fed technologies are highly suitable for large functional components given their high deposition rates.

- Activity based costing seems to be the most used technique to perform product cost estimation of AM products.
- There is no evidence on research of complete AM production systems which include also post processes.

To gain exhaustive understanding of AM based production systems, research institutes and industry should design an AM based system complete with all the necessary post processes and outline all the workers required and the activity involved in the whole production system to have a final product. This will allow to perform an actual, reliable cost estimation of additive manufacturing products.

This review helped also to outline what are the technical and operational opportunities provided by AM if applied in a Defence Support Service context, making the technology highly suitable for this sector featured and constrained by extended and disrupted supply chains.

Moreover, AM is an enabler of design freedom which provides designer the possibility to access new, more sophisticated and complex design forms. This opportunity has resulted in the large adoption of the combination of topology optimisation with AM. Through the topology optimisation of designs, firms can provide components with enhanced functionality such as lightweight, higher performance, reduced sub-assemblies and modularity. Another important factor to be considered in cost modelling for additive manufacturing is associated with additional design costs due to the need to re-design the part to minimize the deposition of supports and deposition time and topology optimisation.

Furthermore, the review on current AM cost models outlined that the most logical and detailed approach to costing AM products is the combination of “Activity Based Costing” (ABC) with process mapping. Nevertheless, current models do not incorporate exhaustively all the costs occurring in an end-to-end AM process, rather these focuses on the solely AM deposition. Moreover, the investigated AM models do not include uncertainty and randomness which are considered rivers of costs in the real world (i.e.

human variability, failure rates). The initial results of the research are considered highly promising. By implementing AM in the Front-end of a DS2, on the platforms, the DS2 performance is dramatically improved. Firstly, non-value adding processes (PDT, ADT) are reduced or eliminated.

Figure 82 - WAAM Systems

The MoD personnel will have access to the AM machine any time during the mission and can print components continuously within the platform and waiting time will be due only to the cycle time of the AM machine, post processes, qualification and assembly.

The concept of operation of the Hybrid AM system is outlined in Figure – 82 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 in Figure – 82 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.

By progressing from the Back-end to the Front-end of a DS2 system, the system is featured with critical environments, extended supply chains and in some cases disrupted supply chains. Next Generation DS2, such as the "Rapid Availability Support System" (RAS2) will exploit delocalised manufacturing opportunities. The service provider and the "Ministry of Defence" (MoD) will benefit from:

- Increased support to the availability given a reduced response time.
- Reduced supply chain complexity given only supplies of raw materials such as powder and wire.
- Reduced platform's inventory levels, providing more space.
- Reduced delivery time of the component as the RAS can be located near to the point of use.

The main constraints are related to the qualification of the parts within a platform.

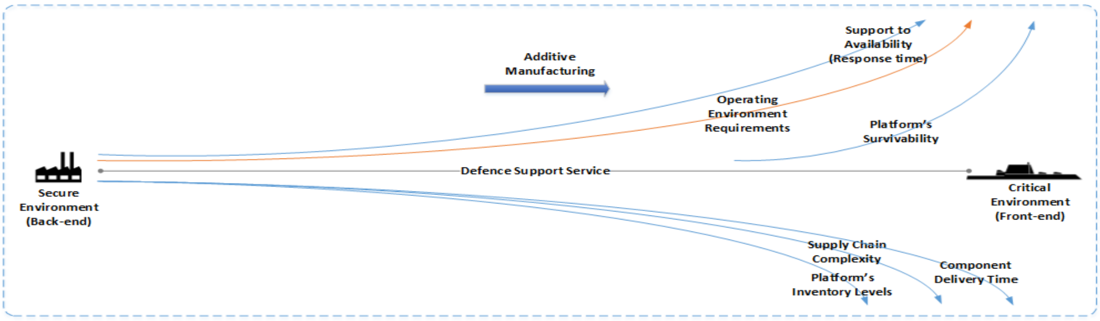


Figure 83 - AM benefits in DS2

AM provides three main advantages which are suitable for the DS2 sector:

- Delocalisation, given the compactness of the technology compared with traditional manufacturing.

- Rapid manufacturing, given its ability to deposit any complex geometry in reasonable times.
- Flexible manufacturing, given its ability to process random geometries without any impact on time and cost.

These three main advantages of AM have a strong fit within the DS2 type of environment given the need for delocalisation within OpEnv with limited space. Moreover, as outlined previously, a platform is featured with an extended number of systems with different components. In fact, the failures may be due to wear or random failures, making it unclear what the demand will look like. This requires a machine which can process rapidly different geometries at a random order without affecting the overall setup time. This paper contributes to the research efforts on Support Services for the defence sector also called “Defence Support Services” (DS2). The framework proposed represents an exhaustive way for carrying out the assessment and putting in context AM within support services. The framework considers the end-to-end process to exploit AM to support systems’ availability. It considers all the different scenarios of the real world, the different AM technologies, post processes and design conversion for AM making it a comprehensive tool for carrying out analytical work and support decision. The results of the research outlined promising benefits from AM applications within DS2.

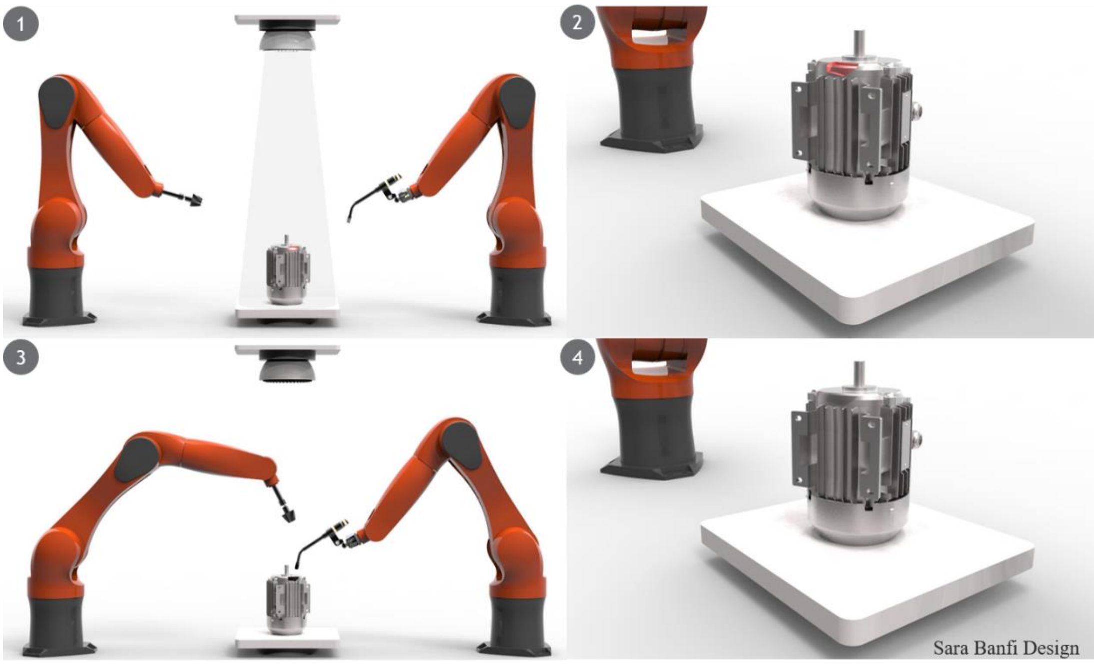


Figure 84 - Concept of Operation

Firstly, the overall system is dramatically improved through the elimination of non-value adding activities, which occur between the Royal Navy, MoD and DS2 provider (ADT and LDT). As the machine is delocalised within the platform and is available without limits, the users can access it whenever a component is required.

The MoD is charged in a second phase, when the platform will return to port from its mission. The second important improvement is the location of manufacturing near the point of use, providing major advantages in terms of reduction of transportation. Considering that in a navy context the major contributor to downtime is the MLDT, this aspect represents the major contributor to improved availability. Given the current shift from spare part contracts to "Contracting for Availability" (CA), the DS2 provider may benefit from improved profitability through the adoption of next generation DS2 based on AM. The third aspect is related to the transformation of the warehouses from keeping physical components to keeping digital 3D drawings stored as CAD files and STL files and powder and/or wire stocks.

9.3 Conclusions and Future Work

This PhD contributes to the research efforts on Support Services for the defence sector also called “Defence Support Services” (DS2). The main contributions to knowledge of this PhD are represented by 1) the System of Interest (SoI) of a Defence Support Service (DS2) which outlines its elements, sequences, links and triggering events, 2) a Conceptual Framework to assess the impact of Additive Manufacturing applications in (DS2), 3) Mathematical Models to estimate the time and costs of AM and 4) an Additive Manufacturing - Decision Support System (AM-DSS) software tool to perform simulations of AM applications in DS2, get real estimates and compare next generation practices with traditional support services. The research approach adopted is adopted from “Soft System Methodology” (SSM) and primary research results are obtained from interviews with experts of DS2 in both academia and industry. Current practices, the framework and the next generation DS2 have been validated with expert’s judgement. The framework proposed represents an exhaustive way for carrying out the assessment and putting in context AM within support services. The framework considers the end-to-end process to exploit AM to support systems’ availability. It considers all the different scenarios of the real world, the different AM technologies, post processes and design conversion for AM making it a comprehensive tool for carrying out analytical work and support decision. The results of the research outlined promising benefits from AM applications within DS2. Firstly, the overall system is dramatically improved through the elimination of non-value adding activities which occur between the Royal Navy, MoD and DS2 provider (ADT and LDT). As the machine is delocalised within the platform and is available without limits, the users can access it whenever a component is required. The MoD is charged in a second phase, when the platform will return to port from its mission. The second important improvement is the location of manufacturing near the point of use, providing major advantages in terms of reduction of transportation. Considering that in a navy context the major contributor to downtime is the MLDT, this aspect represents the major contributor to improved availability. Given the current shift from spare part contracts to “Contracting for Availability” (CfA), the DS2 provider may benefit from improved profitability through the adoption of next generation DS2 based on AM. The third aspect is related to the transformation of the warehouses from keeping physical components to keeping digital 3D drawings stored as CAD files and STL files and powder and/or wire stocks.

The current software tool represents a good starting point for estimating the time and cost of delivering an AM printed component nevertheless the model is featured with some limitations. Firstly, the geometry complexity of the design has an impact on the time of deposition due to increased movement of the deposition nozzle to deposit the features. Moreover, the orientation of the part has an impact on the time of deposition due to the related support volume. Furthermore, an equation would be required to estimate the time of deposition having as input the volume of material. Additionally, build failures may occur resulting in losing time and cost. This should be included nevertheless there is a lack of data of failure rates. During a deposition, the wire might deplete and an operator should replace it. Nevertheless, this is dependent on the part volume and the level of the canister and a standard case is difficult to define. It is reporter by users that higher degree of utilization of the build chamber have a positive impact on the time of deposition as the deposition efficiency increases. Activities related to the 3D Scanner should be modelled as these might consume time. Moreover, the processing time of the acquired data through the 3D Scanner might be higher than the actual acquisition. Finally, the 3D Scanner might not be used in all cases therefore this should be an option in the model.

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Appendix – 1 First Modelling effort

Figure 85 - Module - 1 WAAM Technology

Module 1 focuses on the Additive Manufacturing Technology. The DSS includes a library of Mathematical representations of “Wire + Arc Additive Manufacturing” (WAAM), “Selective Laser Melting” (SLM) and “Fused Deposition Modelling” (FDM). The first Module is employed for Cycle Time (CT) and Product Cost estimation to achieve a Net-Shape deposition (includes machining of waviness). In Figure 85 outlines the “Graphical User Interface” (GUI) for WAAM Technology. The core of the Module is represented by the Mathematical Model which is embedded in the Back-End. The Mathematical Model represents WAAM Technology with an extensive set of equations which have been developed through a technology analysis which includes IDEF0, Data processing and Process Mapping. The Module is semiautomatic and requires the user to provide product information as input such as material type, volume of deposition, thickness of substrate. Moreover, two key variables have been included, these are the wire diameter and “Wire Feed Speed” (WFS). The rates box in the bottom left side of the Module, allow user to tailor the computation to the type of case study. The ‘output’ of the Module are a detailed “Cost Breakdown Structure” (CBS) of the deposition, performance data such as Deposition Rate, Deposition Time and Machining Time. Furthermore, the curves of the variables WFS and Wire Diameter have been plotted to show how the cycle time drops.

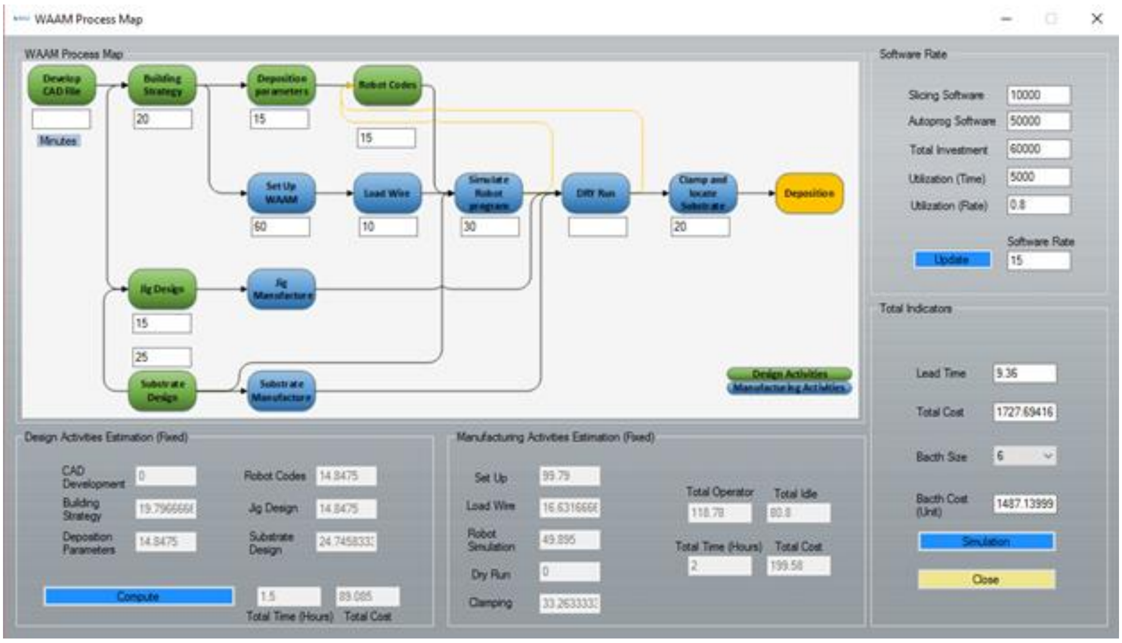

Figure 86 - Module - 2 Design and Set Up

Module – 2 outlined in Figure 87 has been included to model the end-to-end process of obtaining a net shape deposition. This allows the user to achieve a more comprehensive, exhaustive and accurate estimate on the time and costs of AM. AM may require extensive efforts in the Design, Data processing and setup stage. Hours of engineering and software are consumed during these stages and have to be included within the estimate. Has to be outlined that AM is usually employed to exploit Design Freedom and access new geometries to obtain increased functionality, efficiency and reduced material usage. In order to redesign the components, firms employ extensive use of Topology optimisation software and AM Design Software tools. The Module allows the user to include early stages of capital investment in software and select where these are consumed, moreover rates of Engineers and technician are included. The user has to INPUT the time in minutes for each activity and obtain as OUTPUT the Design Activity Breakdown and Manufacturing Activity Breakdown. Finally, AM allows users to deposit concurrently more products and is featured with some fixed costs. The combination of these two aspects allows users to exploit economies of scale opportunities which are quantified in the “Total Indicator” Box where users can INPUT the batch size and see how the Product Cost estimates reduces with increase Batch Size.

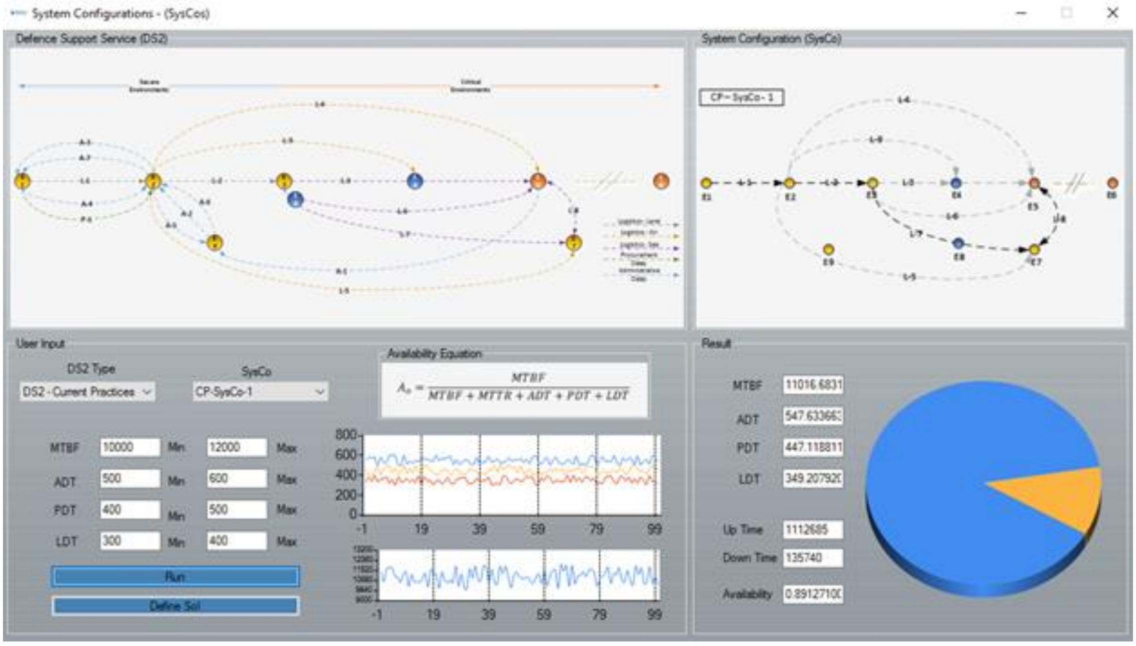

Figure 87- Module - 3 System Configurations

Module – 3 outlined in Figure 87 represents the “System of Interest” (SoI) of a Defence Support Service system (Left Box) and its “System Configurations” (SysCos) (Right Box). Through this Module, outlined in Figure 87, the user can simulate probabilistically current and next generation practices, test available SysCos and generate significant and reliable results in terms of Time, Cost and Availability. The Module is designed for two sources of randomness, external through the input of uniformly distributed inputs (min, max) and internal through the implementation of a Monte Carlo pseudo-random generator. The simulation assumes no stocks are held over the DS2 system and it is not possible to observe the changes of states of the system elements with the progression of time (static model). Through the “DS2 Type” library the user can select between current and next-generation practices. In current practices manufacturing occurs within the back-end of the system and the available SysCos are related to the front-end logistics (Nr 5 SysCos). In next-generation practices the user can select both the location of the AM unit which can be deployed till the support vessel and the related logistics options (Nr 6 SysCos). Finally, the Module allows the user to test each available SysCos and compare traditional and next generation DS2 systems outlining solid estimates on Time, Cost and Availability.

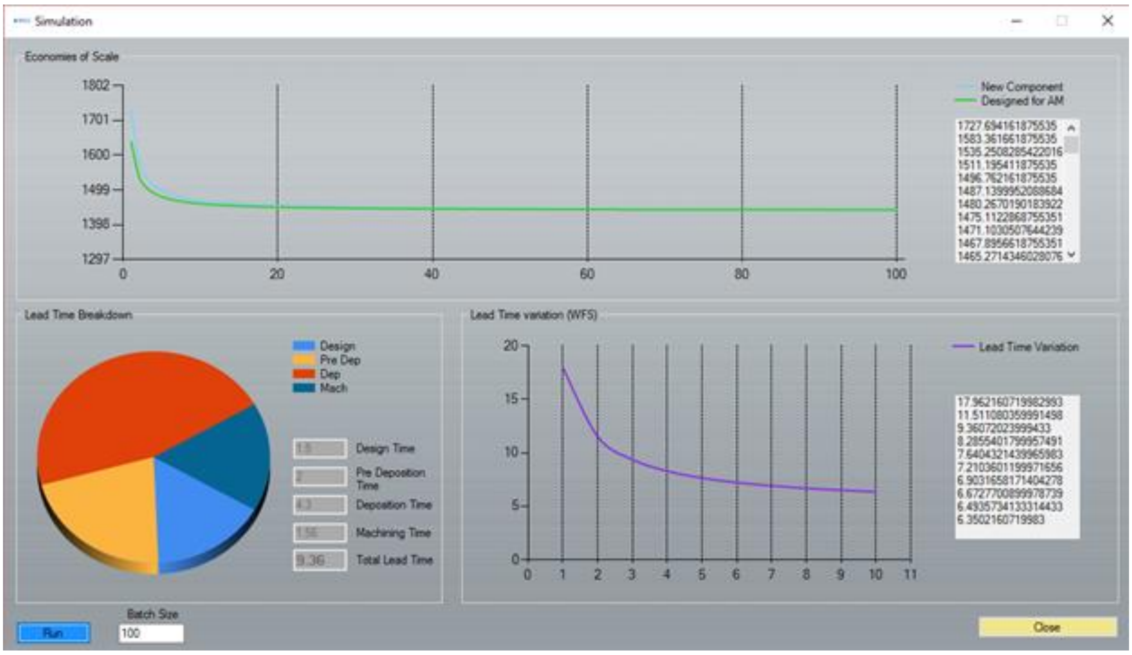

Figure 88 - Module - 4 Results

Module 4 outlined in Figure 88 recap the results of the simulation.

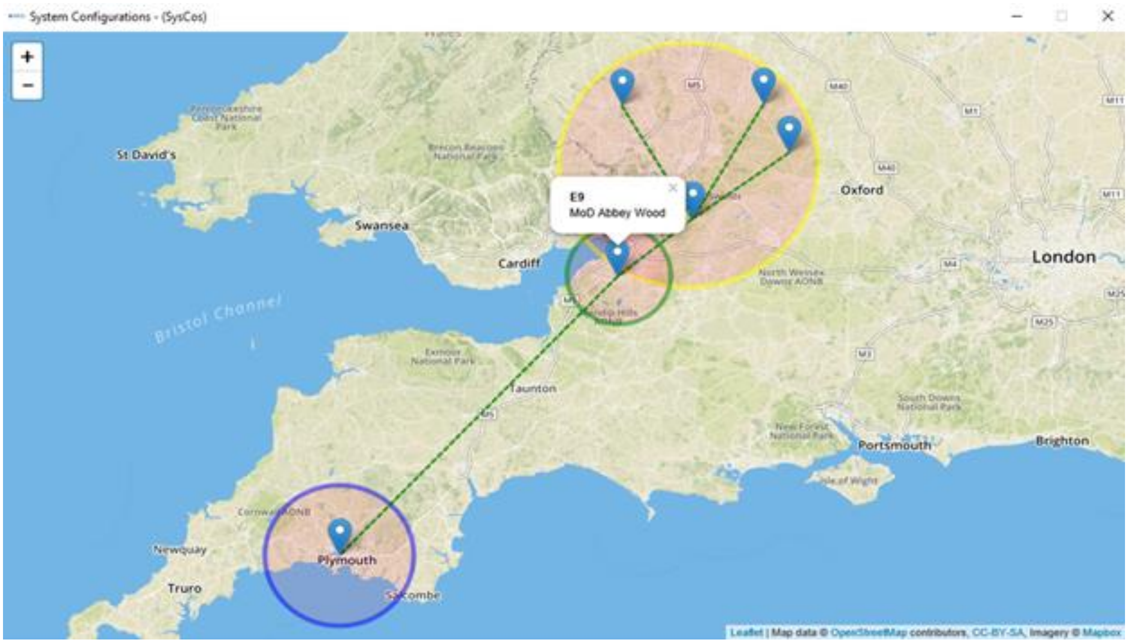

Figure 89 - Module - 5 Interactive Map

Module 5 outlined in Figure 89 allows users to drop pins in an Interactive Map.

Appendix – 2 Mission Analysis

Mission Analysis aims to define exhaustively the high level environment in which the Royal Navy operates and available opportunities arising from "Additive Manufacturing" (AM). The activity is broken down into two distinct spaces:

- *Problem Space:* which outlines qualitatively the various and at different level challenges faced by the Royal Navy. Experts have been encouraged to "input" actual and current challenges faced by the Royal Navy.

- *Opportunity Space:* which exploits current and future opportunities arising from "Additive Manufacturing" (AM). Experts have been encouraged to adopt an elastic and creative approach and abandon constraints given by the current limitations and maturity of AM.

Prior to the start of the activity, experts have suggested some suitable next generation applications of AM in the Royal Navy such as: 1) printing mechanical components, 2) printing structures and supports, 3) printing prosthetics, 4) repairs, and 5) printing unmanned vehicles. Moreover it has been clarified that the aim is *"to define the concept of a turn-key system"* in which AM may be the core technology but not limited to.

In order to obtain reliable results and different perspectives, key experts of the UK Defence Value Chain have been involved. The list of experts:

Organisation	Position	Experience
Navy Command Headquarter (NCHQ)	Commander Royal Navy	30
Babcock International	Through-Life Support Manager	30
Babcock International	Operational Support Manager	33
Defence Equipment and Support (DE&S)	Technology Maritime Delivery	30

Defence R&D Firm	Technical Lead	17
Babcock International	Technology Acquisition Lead	10

Table 20 - List of Experts

The elicitation process has been carried out in two forms. The first form involved a workshop which lasted 5 hours in which participants went through an individual session where they had to “think on their feet” and following a group session where collective brainstorming has been carried out. The second form involved the emailing of structured charts with a related guide where experts carried out the activity individually.

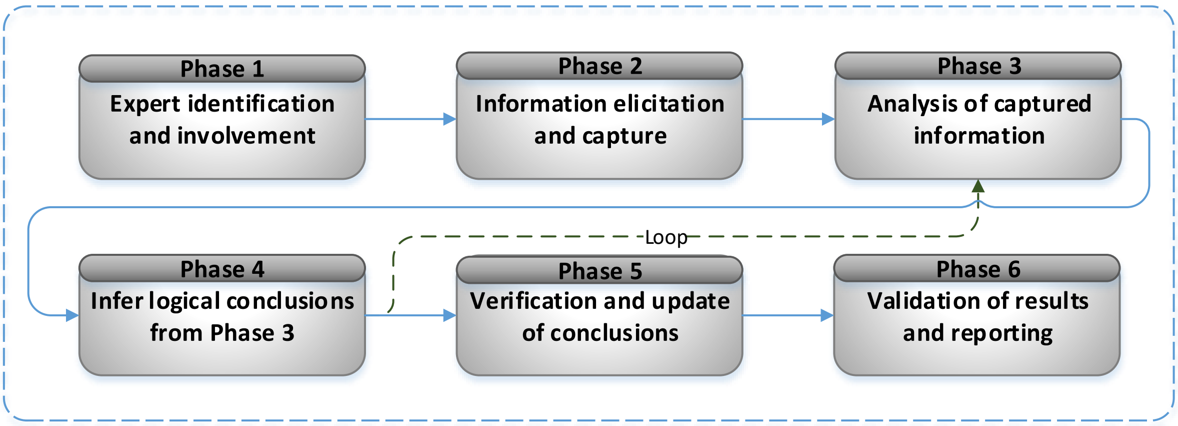

Figure 90 - Research Approach

The research approach adopted in order to capture the expertise and develop conclusions is outlined in Figure 90 - Research Approach. The research approach is made of 6 phases:

- Phase 1: organisations of the UK Value Chain have been contacted and requested to nominate an experienced and reliable source of expertise.
- Phase 2: the information elicitation process has been carried out through an induction of the activity aim and through the use of structured charts, moreover the audio of the sessions have been recorded.

- Phase 3: once the information has been captured the results have been analysed and reorganised.

- Phase 4: once the information has been reorganised it has 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.

- Phase 5: the draft has been sent to the experts for verification and where necessary experts made recommendations on how to improve it.

- Phase 6: the results have been validated and reported.

1. Problem Space Analysis

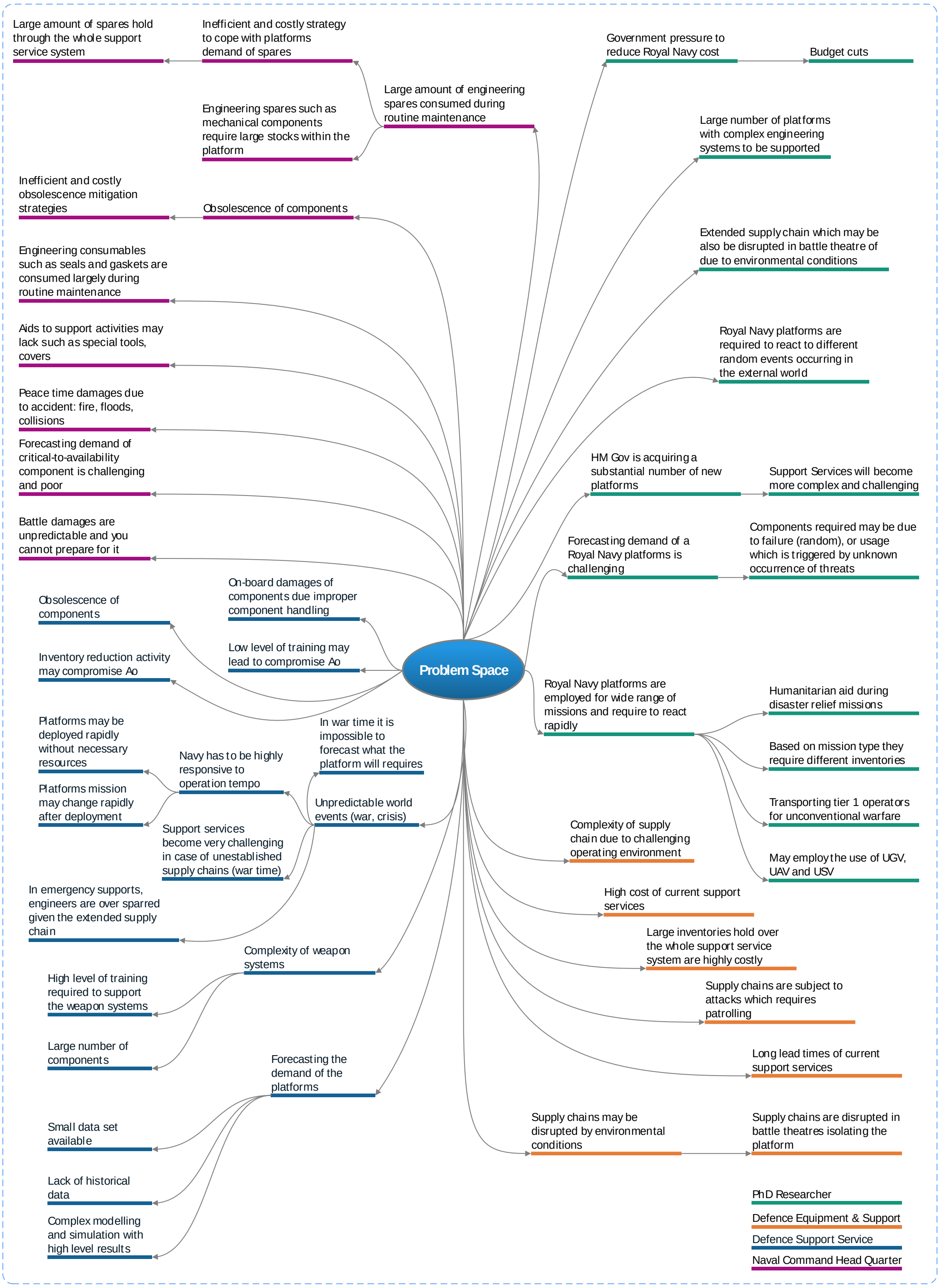

Figure 91 – Inputs received

The “Royal Navy” (RN) operates a vast number of defence platforms, today 74 and by 2025 around 37 new platforms will be acquired and commissioned (MoD, 2015). The platform’s operation and support activities accounts up to 70% of the total cost of ownership and are carried out in a hybrid way by the RN technical department and by “Defence Support Service” (DS2) providers (DoD, 2014). The platforms have 3 operational stances: 1) deployed 2) operational but not deployed and 3) non-operational. Each of the stances require different level of support activities some of which are carried out continuously as routine maintenance and require a large amount of consumables. The RN platforms interact with the external environment through a vast number of “Complex Engineering System” (CES) which are critical to the platform’s survivability and lethality. CES may be featured with advanced technologies and a vast amount of components such as the “Highly Mechanised Weapon Handling System” (HMWHS) which is made of 17 sub-systems and 1.500 components. To support CES, technicians need to be skilled and trained and require also special tools to operate.

Moreover the platforms are featured with space scarcity which has to be partitioned between: 1) critical-to-availability components, 2) tools and consumables, 3) humanitarian aid 4) other smaller platforms 5) small arms, 6) unmanned vehicles and consumables for the crew which is the mainly limiting factor of a platform’s autonomy (Busachi et al., 2015). In order to keep platforms operational and its systems available to operate when required to do so, the RN and DS2 providers need to establish support service systems in order to provide the platforms what they require wherever they are in terms of location and operating environment (Busachi et al., 2016a). Support service systems are complex, costly and inefficient systems which operate through different challenging operating environments such as war theatres where hostile entities with firing power are present. The supply chain of the support service system may need to be patrolled during war in order to avoid disruption. Moreover, as the platforms are operating in the sea these supply chains may be disrupted also by adverse weather conditions. Another case of supply chain disruption is the battle theatre where a platform is actively engaging hostile entities, in this case the platform is isolated and cannot be supported. Furthermore in the battle theatre, platforms may be subject to battle damage which may compromise capability and structural integrity and there is no way to prepare for this (Busachi et al., 2016a).

RN platforms are required to be highly responsive to operation tempo, therefore the platforms and the crew have to be highly resilient to fast changing operational environments and missions. Based on mission type the platform has to tailor its inventory level but in some cases this is not possible given the urgency of deployment implying the platform to have partial or limited resources to accomplish its mission. Moreover in case the platform has to operate in "new waters" the support service system may be unestablished adding more challenge to the support.

Given the criticality of support activities to keep the platform operational, both the RN and DS2 use modelling tools to forecast in advance what will be required, when and where. Nevertheless modelling the demand of 74 platforms requires an immense effort and highly complex modelling tools which may not be accurate enough. Also, accuracy of forecasted platform's demand is based on quality and detailed data of historical usage which is difficult to capture, store, classify and use. It has to be outlined also that systems are continuously upgraded or replaced in which case there is no data available. Moreover, in case of war time the modelling effort becomes ineffective as the platforms behaviour is uncertain and dependent on hostile initiatives.

Another important aspect is related with the long lifetime of the platforms, which may be required to operate for 50 years. "Original Equipment Manufacturers" (OEM) involved in the development and support of the platforms and their systems may go out of business, abandon the production of the systems or components due to new designs or technological advancement. This leads to obsolescence cost which affect dramatically the "Ministry of Defence" (MoD, 2015).

Moreover, the platforms are subject to accident such as fire, floods, collisions or grounding which may compromise CES or structures. As for battle damage, there is no way to plan the required materials, components and structures necessary to recover capability.

In order to cope with the above environmental challenges, the Royal Navy and DS2 providers have put in place all the necessary mitigation strategies which on one side are the only possible solutions and on the other side are considered not responsive enough and costly. For example components and spares are spread over the whole support service system in order to reduce the “Logistic Delay Time” (LDT) which has the highest impact on operational availability. Moreover forward bases and support vessels are deployed and supply chains are established and maintained in order to improve the support to the platforms (Busachi et al., 2016a).

Supporting RN platforms and its CES is a critical and necessary activity featured with uncertainty, complexity and ambiguity. The platform’s and CES’s availability is put at risk by different random events which makes challenging the support activity. Required materials, tools, spares, critical-to-availability components, structures and consumables are highly dependent on unforeseen events which are difficult to predict or control. Moreover it is impossible to store all the necessary materials within a sole platform due to space constraints. Given the nature of DS2 systems, the following Additive Manufacturing’s (WAAM) benefits seems to fit very well: 1) compactness of technology making it deployable, 2) high deposition rates, 3) ability to process random geometries, 4) ability to print also large, fully dense metal components, 5) low product cost.

2. Opportunity Space Analysis

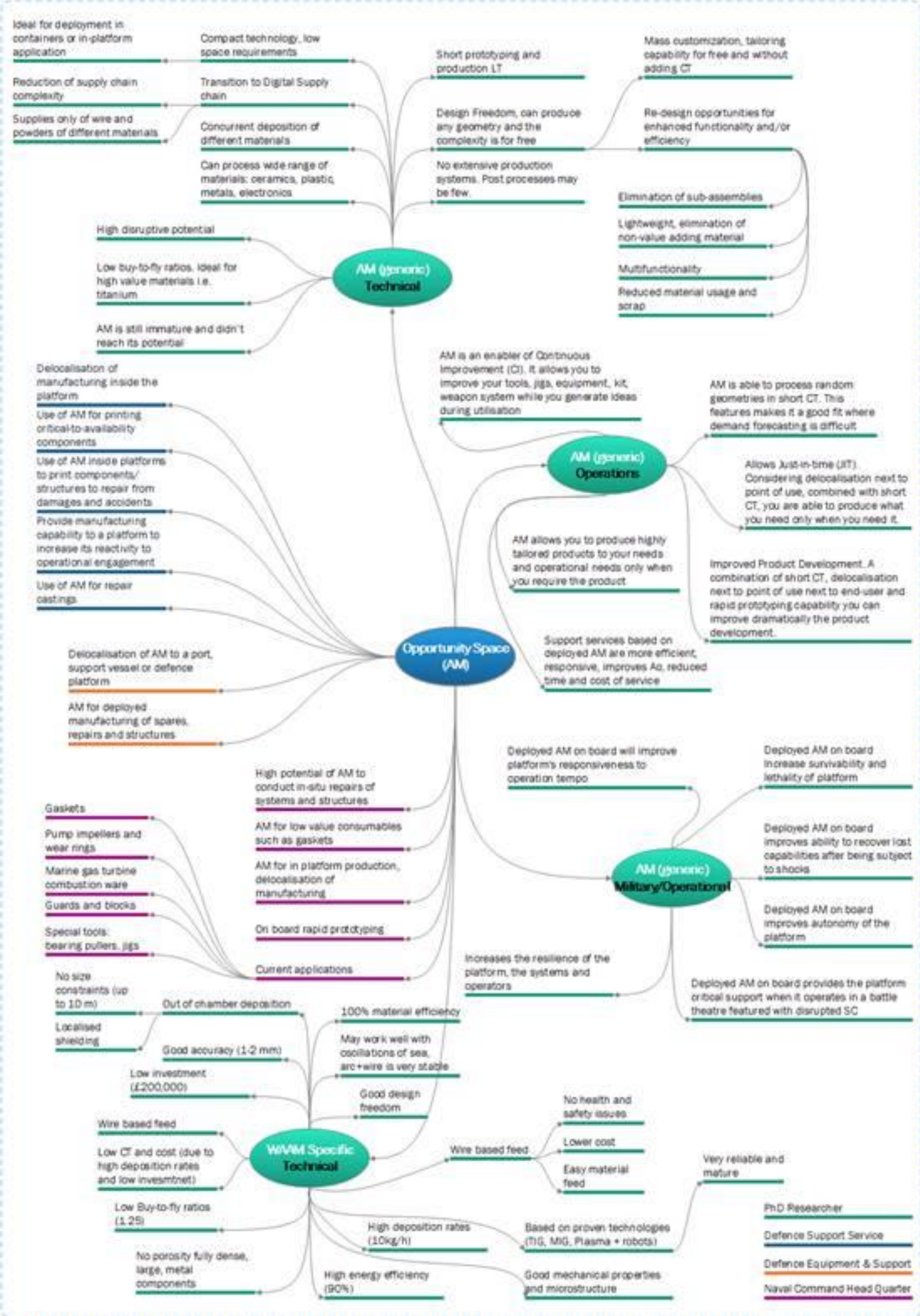

Figure 92 - Inputs received

The inputs received by the NCHQ, DE&S and Babcock International share similarities. The key players of the UK Defence Value chain outlined the same vision on AM to be exploited for delocalisation of manufacturing near the point of use or in different stages of the "Defence Support Service" (DS2) system such as port, support vessels or forward bases. The vision of AM in DS2 are mainly: to print, next to point of use, critical-to-availability components in order to eliminate or reduce the "Logistic Delay Time" (LDT) and improve availability of "Complex Engineering Systems" (CES), to repair components and structures when battle damages or accidents occur and recover capability, to print low value consumables inside the platform in order to reduce some inventory (Busachi et al., 2016a). Other applications outlined are, to use AM in order to solve obsolescence issues and also for repairing castings. The NCHQ sees immediate application of AM to produce gaskets, pump impellers, wear rings, combustion ware, guards and blocks and special tools required during on-board repairs. AM (generic) technical benefits have been outlined such as design freedom, compactness of technology, physical supply chain complexity reduction, digital supply chain, delocalisation, concurrent deposition of different materials, ability to process metals, plastic, ceramics and electronics, re-design for enhanced functionality or efficiency, elimination of sub-assemblies, multi-functionality, mass customisation. These benefits are shared with different levels, amongst most of the available process methodologies such as Laser Cladding (LC), Wire + Arc Additive Manufacturing (WAAM), "Fused Deposition Modelling" (FDM), "Selective Laser Melting" (SLM). According to Busachi et al., (2016b) the above AM process methodologies are the most promising in the future for the "Royal Navy" (RN) needs. Nevertheless, even if AM processes such SLM, FDM and LC have been already commercialised these are still immature and will improve dramatically in the future. Moreover these are too problematic, not efficient, costly, not tailored to the RN needs. More specifically SLM is not suitable for short to medium deployments within containers or within a platform due to its sensitivity and lack of robustness to cope with critical environments (require stable temperature, humidity and no vibration), very long cycle times given by slow deposition rates and inability to cope effectively with design complexity. SLM machines need to be calibrated every time they are subject to movements, moreover calibration takes up to 3 days. Furthermore the powder bed nature of SLM makes its ineffective in vibrating and oscillating environments. WAAM process, even if still not matured till commercialisation, is based on “Gas Metal Arc Welding” (GMAW) i.e “Tungsten Inert Gas” (TIG), “Metal Inert Gas” (MIG) and Plasma and industrial robots for controlling the deposition. WAAM has an extended number of benefits outlined in Figure 92 - Inputs received. The 3 most important benefits of WAAM are 1) reliability, maturity and proven repeatability of its sub-technologies, 2) very high deposition rates with related low CT and 3) stability of arc + wire solution during vibrations and oscillations of platform. Nevertheless WAAM is still under development in Cranfield University and cannot be considered user friendly as it needs strong know how and expertise in order to be operated.

Furthermore, AM (generic) operation aspects have been outlined. These AM operations aspect are based on “Manufacturing System Engineering”, “Lean Manufacturing” principles and “Lean Product and Process Development” and are possible due to the delocalisation of AM production next to the point of use and through the involvement of the end-user:

- AM as an enabler of “Continuous Improvement” in the work place: RN operators, while deployed carry out their daily activities (with standard tools, jigs, equipment and kits) through which they mature a direct experience. During this experience they might develop/generate ideas in order to improve a process. If a platform has manufacturing capability based on AM they can convert ideas into functional products.

- AM is an enabler of Design Freedom, it is able to print rapidly any kind of geometry without the need to setup the machine or change tools: this aspect fits very well if we consider that AM is deployed in a platform to “serve” various “Complex Engineering Systems” (CES) made of an extended number of components which all differ one from another in terms of geometry. A sole AM machine is able to manufacture all of the components when these will fail.

- AM as an enabler of improved Product Development: similar to the first point, AM allows to improve the Product Development. End-users, through the utilisation or direct experience develop/generate naturally ideas to improve their daily routine. AM as an enabler of CI is given by a combination of delocalisation of manufacturing next to the point of use, involvement of end-user (which detain the direct experience) in the PD and rapid prototyping capability to test the designs in the early stage.

- AM as an enabler of "Just-in-Time" (JIT): Considering the delocalisation of manufacturing within the platform, the "Logistic Delay Time" (LDT) is eliminated or dramatically reduced, moreover AM allows to achieve short CT of production. This combination allows to establish JIT principles which allows you to reduce the stocks of finished goods and produce only the components that you require and when you require them.

- AM as an enabler of mass customisation: AM allows you to produce highly tailored products to your needs and unique features. This aspect is fundamental when you require special tools to perform an operation, when you have to produce a prosthesis tailored to the human body unique features or to provide special tools/small arms/body armours to tier-1 operators.

- AM as an enabler of improved Defence Support Services: through the delocalisation of AM within a platform, DS2 systems improve dramatically in terms of efficiency and cost.

3. Logical Inferences

This section aims to derive preliminary logical conclusions on the Mission Analysis activity. These preliminary conclusions outline suitable and promising applications of AM in the context of the Royal Navy. In order to do this a multidisciplinary approach has been adopted as outlined in Figure 93 - Multidisciplinary Chart which groups together four distinct, but interconnected areas: 1) AM technical aspects, 2) AM operations aspects, 3) Royal Navy operations type, 4) Royal Navy challenges and in the centre 4) Most promising application.

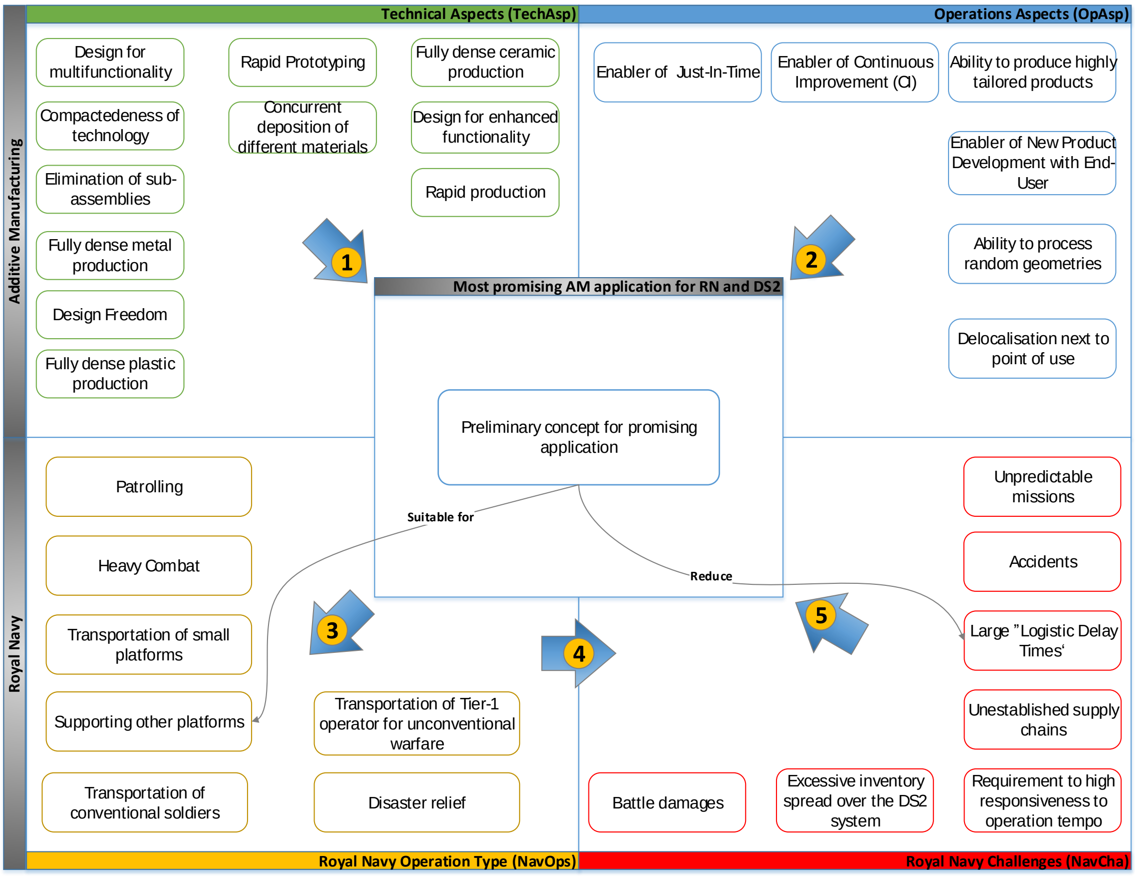

Figure 93 - Multidisciplinary Chart

Area 4 – "Most promising application" is carried out using the following logic: *"Considering "these" AM technical aspects plus operations aspects, within "these" type of RN operation and considering these RN challenges faced, a system based on AM could be developed to accomplish this "aim" which will solve or reduce "these" RN challenges and is particularly suitable for "these" types of RN operations".*

Based on this approach, the following promising AM application has been identified:

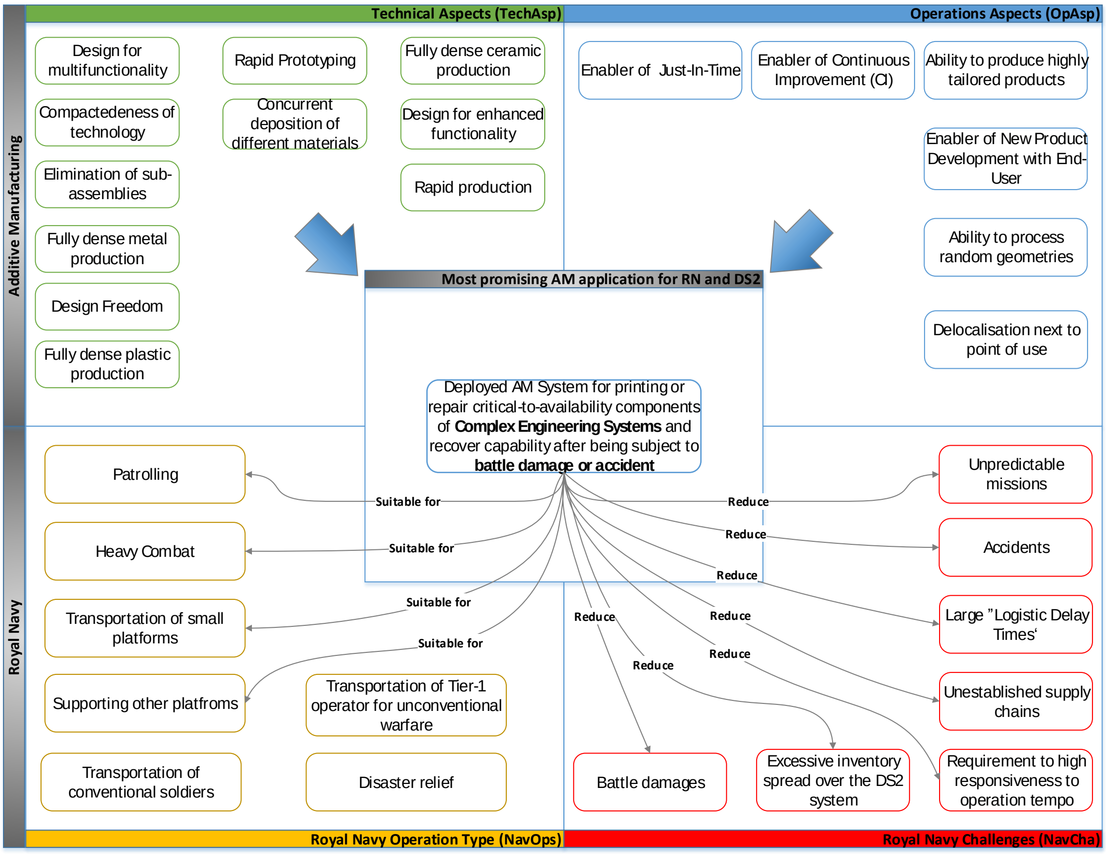

Figure 94 - Support to Complex Engineering Systems

"To exploit AM opportunities to support "Complex Engineering Systems" (CES)": providing AM capability to a defence platform, support vessel or forward base to print or repair failed critical-to-availability components of CES and print new components or structures to recover capability after being subject to shocks. Through the delocalisation of manufacturing to the front-end of a defence support service system the "Logistic Delay Time" (LDT) is dramatically reduced or eliminated, the inventory level drops given the use of AM only when the components are required, availability of CES increases, the responsiveness of the DS2 improves dramatically and costs related to keeping the CES available and ready to operate drop dramatically. Moreover inventory on the platform can be reduced as AM is able to process random geometries in reasonable cycle times. Furthermore, this capability will allow the platform to recover from damages due to battles and accident.

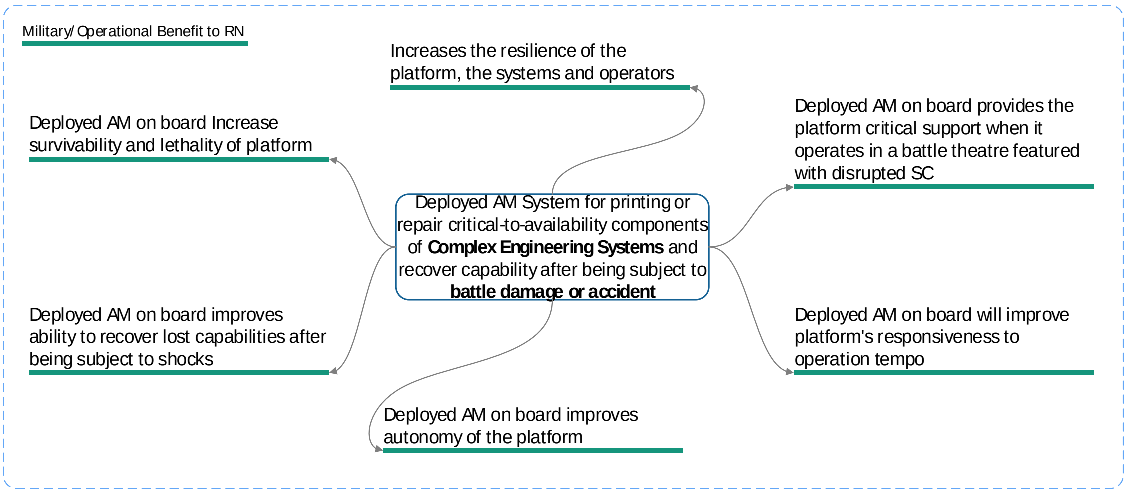

Figure 95 - Military Operational benefit to RN

As outlined in Figure 95 - Military Operational benefit to RN this type of application has also some "military" or "operational" advantages. A Royal Navy defence platform is required to be highly responsive, multipurpose (can be employed for different missions), able to deliver lethality and survive in hostile environments and be autonomous for long periods (months). If AM is deployed within the defence platform the above military or operational aspects can be improved dramatically. Through this approach it was possible to outline other promising application of AM for the Royal Navy:

- Deployed AM system to support disaster relief missions, such as printing structures, prosthesis, medical disposable products tailored to the unique geometries of the human body. Also to print simple plastic components used for medical applications such as plastic pipes and valves and general fittings which may be required in the environment affected by disaster.

- Deployed AM system to support Tier-1 operators employed in unconventional warfare. The aim of the system is to make tailor made kits, weapon systems and body armours based on the operator's unique requirements and mission needs.

- Deployed AM system to print new unmanned vehicles for ground, sea and air application and also be able to repair them if damaged in the battlefield.

Appendix - 3

Navy Command Headquarter (NCHQ)	
Ship Damage Control/Repair	Peacetime accidents for example fire and floods caused by equipment/system failure, collision or grounding result in damage to ship systems and structures. Temporary measures will save the ship and even return it to the fight. Longer term repair invariably requires access to shore side ship repair facilities.
Engineering Consumables	A vast range of seals and gaskets are consumed on-board ships during the course of routine maintenance and repair. Currently these are stocked on-board, held in the supply chain or demanded from the supplier to match consumption. Predicting demand is difficult and tasks can be held up for the want of a simple component.
Engineering Spares – Single Material	A vast range of mechanical spares are consumed on-board ships during the course of routine maintenance and repair. Currently these are stocked on-board, held in the supply chain or demanded from the supplier to match consumption. Predicting demand is difficult and tasks can be held up for the want of a simple component.
Aids to Operation and Maintenance	During the course of maintenance and repair on-board there are occasions when protective covers, blanks and special tools are required.
Obsolescence	Ships built today could expect to be in service for 50 years and it is unlikely that many of the original OEMs would still be in business. Obsolescence has been tackled in a number of ways; replacement of the equipment by new when it becomes too expensive to support, lifetime buys of spares or re-manufacture.

Table 21 - NCHQ Inputs

Defence Equipment and Support (DE&S)	
Cost, latency and vulnerability of supplies	To order, produce/procure, supply and deliver a particular spare to a deployed ship can be time consuming and incur large costs arising from for example; transportation / protective packaging / certification / customs legislation and logistics. Extant supply chains are also vulnerable to attack and /or external disruption from a number of active and passive sources. Conversely, to carry large inventories of spares at forward bases or at sea, is comparably expensive and can be impractical.

Table 22 - DE&S Input

PhD Researcher	
Government pressure and budget cuts	Government is increasing the pressure on MoD in order to improve its operations and lower its costs. HM Gov has increased the employment of strategic and technical consulting firms in the past years in order to develop performance improvement projects. MoD in strongly involved with McKinsey, Deloitte, PWC, Atkins, Jacobs in order to reduce its costs.
Increase of Nr of Platforms of the Royal Navy	The MoD will increase its number of defensive platforms of the Royal Navy. Currently it holds 74 platforms and will acquire other 37 by 2025. With the increase of Nr of platforms the support service becomes more complex and costs will increase consistently. It will require to expand its current team, operations and facilities.
Forecasting the demand of spares	It is very difficult to forecast the demand of the spares required by a platform. This is mainly given by the extended number of components operating on the platforms and the unpredictability of random failures and inability to forecast the utilisation of the complex systems. Current strategy is to stock critical-to-availability components within the platform but unfortunately defence platforms are featured with space scarcity. Moreover components subject to failures and wear are purchased in advance and stored in warehouses in order to eliminate the procurement lead time.
Extended and disrupted supply chains	Royal Navy platform may operate everywhere in the World and can be featured by extended and disrupted supply chains. In a battle theatre the platform is isolated and has to rely on internal resources in order to support its complex systems. Moreover extended supply chains results in high cost for delivery and long lead times.
Obsolescence of components	Defence platforms are affected by obsolescence costs. It is widely reported that various component become obsolete before the platform gets commissioned. The main strategy of MoD for mitigating this risk is to acquire and stock large inventory of components in warehouses. This result in high costs. Also, when MoD runs out of spares has to look for manufacturers which are willing to run production of few batches resulting in high cost of product.

Table 23 - PhD Researcher Input

Defence Support Service provider – Babcock International	
Reconciliation and reduction of inventory	There is a strong drive to reconcile and where possible reduce stock holdings, this causes an issue as modelling can look at historical usage but if deviation from the historical is not factored in then surge presents a significant risk to operational availability. Surge is often the result of unanticipated or uncommunicated change to operational tempo driven by difficult to predict world events.
Damage to stored items on board platforms	Storage on platforms is limited, without a sufficient understanding of the fragility and special handling needs of items being stored some items may be being damaged at depot, transit and platform levels.
Increasing number of diverse operational stances	Platforms broadly could be viewed as having three operational stances (deployed, operational but non deployed and non-operational (refit, deep maintenance, etc.). Today's RN now also have reduced manning, lay-up and training ship stances. These newer additions are as yet not fully understood and as such the impact on sparing yet to be determined.
Small data set from which to make modelling decisions	In many cases there are a relatively small number of equipment comprising the total population so inventory levels driven by anticipated corrective maintenance can take a significant timeframe to achieve credibility. When the equipment is complex it may be the case that diverse failures mean that many items never justify fleet wide provision but still carry high risk to operational availability.
Obsolescence, strategic buys and price breaks	Defence equipment (even COTs derived) will suffer obsolescence and to overcome this a common approach is strategic buys. The number of items purchased can be strategic based on usage and availability but also sometimes the price breaks offered by the supplier can also drive alternative inventory levels.
Emergent requirements	When arranging engineers to support a deployed platform careful consideration with respect to the required spares must be taken. This often leads to over sparing to ere on the side of caution. These additional spares either need returning back to the UK or are left on the platform, become "come in handy spares" and over a period of time are lost.

Table 24 - DS2 Input