Integrating Additive Manufacturing to Support Temporarily Self-Sufficient Systems

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ABSTRACT

For systems such as ships, boats, oil rigs, research stations, but also self-sufficient units for which independence plays an overriding role in the capability domain, new approaches developed at the Manufacturing Technology Laboratory of Helmut Schmidt University, University of the Federal Armed Forces Hamburg, can increase self-reliance and self-sufficiency. Experimentation of this logic for integrating additive manufacturing technologies to support intermittently self-sufficient systems was conducted with the German Navy. By means of a layer model and targeted support with additive manufacturing, the self-sufficiency and thus the resilience of ships and boats can be increased. The level model is based on the military structure and divides the various additive manufacturing processes into so-called levels. These are structured like a pyramid. In the lower level are the representatives that are less complex and have a high prevalence within the industry and semi-professional sector. In the upper levels, the complexity of the processes increases due to aspects such as occupational safety, training requirements and expenditure in the overall process chain. In this context, additive manufacturing capabilities integrated in the system, e.g., on board, have the effect of extending self-sufficiency. In contrast, the level integration of additive manufacturing components outside the system, e.g., in ports, shortens the resupply time significantly. Experimental investigations on this topic have been carried out through simulation, as well as on board of ships of the German Navy. The integration of the first and lowest level of additive manufacturing is in progress.

1.0 INTRODUCTION

In recent years, additive manufacturing techniques have been presented as forward-looking and new manufacturing processes in the maritime sector. In the process, floating platforms were mostly supported from shore. An integration of simple 3D printers on board maritime units of the German Navy was carried out in the first quarter of 2021 by the Manufacturing Technology Laboratory of Helmut Schmidt University, University of the Federal Armed Forces Hamburg, in cooperation with the German Navy. Here it was possible to test on three different ship classes: combat support ship, frigate, and corvette. The influence of 3-D printing on board was demonstrated by mitigation of short-term material bottlenecks directly on site by interim components for needs-based repair. The greatest advantage can be reached by integration of on-board systems and, in a supportive manner, shore-based reach back. Since the resources for setting up and using additive manufacturing systems with a higher degree of complexity in terms of occupational safety or also danger due to the substances used (e.g., powdered starting material) as well as the required post-processing, are limited, such systems can only be operated on land.

A framework for additive manufacturing within an organisation such as the German Navy on the one hand strengthens the resilience of temporarily self-sufficient systems such as ships through integrated manufacturing facilities, and on the other hand minimises supply time and downtime by supporting them with high-quality components from shore.

Additive manufacturing is a generic term that covers a variety of manufacturing processes that have in common that they work layer by layer. There are many specific differences within the process family, which in turn lead to different areas of application and possibilities. These basic principles are generally covered in specialist literature such as Gebhardt [1] or Fritz [2], or are also comprehensively documented in standards such as DIN 8580 and DIN EN ISO/ASTM 52900. However, they are usually only available to inclined technical personnel. This in turn leads to the fact that personnel involved in the process who do not have sufficient knowledge of additive manufacturing come into consideration as a possible point of failure. For example, components manufactured using the fused filament fabrication process require a different post-processing procedure and peripheral equipment than components manufactured using the selective laser melting process. Due to the demands of the processes on their environment, not all of them are suitable for on-board operation or at sea. The different approaches to resources can therefore lead to distortions in the procurement and logistics process. For better understanding, a simple organization-specific classification of the processes is therefore proposed, which enables better communication in the field of additive manufacturing across divisions.

With all additive manufacturing methods, a reliable upstream and downstream process chain is required to produce usable components. This includes the design methods, simulation processes and preparation of the data for the actual additive manufacturing process, as well as the removal of the components from the machine platforms and their post-processing including finishing [8].

In general, systematic procedures for the qualification of materials, manufacturing processes, development methods and quality assurance processes are provided in highly safety-critical and certification-relevant industries such as ship building, aviation, or the railway industry. In addition to the applicable standards, maturity models such as the Technical Readiness Level (TRL) model according to Mankins [9] from the aerospace industry can be used for orientation. The maturity models usually only indicate the technological status and the level of technical maturity, but not the methodical development procedure, which often varies depending on the industry and organization. In addition to technical validation, economic and ecological aspects must also be considered. This also applies to reverse engineering, which is focused on the substitution of components for obsolescence management and spare parts supply within the German Navy. Furthermore, the legal conditions relating to product liability, property rights and intellectual property must always be observed when replacement components are manufactured by the operator of maritime systems. Of course, this does not only apply to maritime and military applications, but is generally transferable to other branches, products, and applications.

Especially in the maritime sector, the designated approval processes and systematic development procedures play a central role. Therefore, the introduction of new technologies, such as additive manufacturing, with new materials, manufacturing processes, design methods and testing processes, often involves a great expenditure of resources and time. In addition to the manufacturer and the operator, the regulatory authorities must also gain a holistic understanding of the technology with its properties, opportunities and, above all, limitations. In all places, this requires qualified personnel, which is a further challenge. For this reason, professional training and further education concepts should be developed and implemented directly with the introduction of such technologies.

1.1 Categorizations for Additive Manufacturing Processes

There are various classification options for additive manufacturing processes. These have already been worked out in preliminary work and will be summarized here. According to Gebhardt [1], machines are divided into fabbers (digital fabricators), desktop printers, professional 3D printers, production 3D printers and industrial 3D printers. Then the categorization is based on the the raw material, e.g., wire, paste or foil. Finally, a distinction is made based on the physical mechanism of layer formation. DIN 8580 [3] categorizes manufacturing processes in general. Additive manufacturing is included in group 1, primary shaping. It is divided into binder jetting, directed energy deposition, material extrusion, multijet fusion, powder bed fusion and Vat Photopolymerization. [4]

1.2 Classification Schematic – Pyramid

Figure 1 shows the pyramid as a schematic representation of the classification of additive manufacturing processes according to dissemination and complexity.

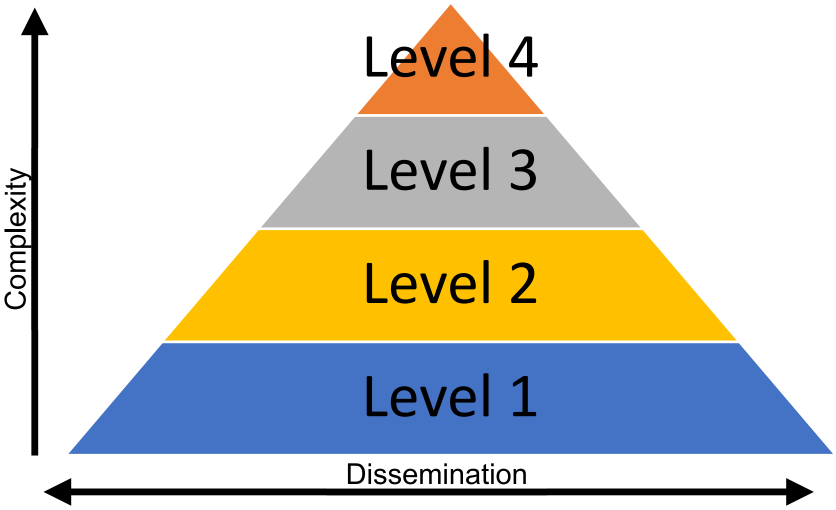

Figure 1: Pyramid with categories for additive manufacturing – Level 1 widespread and less complex technologies in contrast to Level 4 technologies with a high level of complexity and not very widespread due to the specific use, based on Hartig et al. [4].

In the example shown here, additive manufacturing processes are divided into four levels. Level 1 is characterized by

- low complexity in terms of use,
- low resource utilization in terms of labor, energy, space,
- the operator only needs a short general training course on additive manufacturing,
- use on board of boats and ships is possible.

Processes and corresponding equipment assigned to Level 2 are characterized by

- a higher complexity of use,
- peripheral equipment needed for the overall process,
- higher demands on personnel and plant-specific training,
- higher resource consumption in terms of energy and space,
- possible use on board of ships.

Level 3 processes are required to produce components with high complexity and material requirements. Due to process characteristics such as the use of powder as a raw material or other work safety-related restrictions, use on board military ships is unlikely to be efficient. In the overall concept, these processes are needed to mitigate logistical constraints and to support ships and boats in operation with the needed components. Furthermore, the resources for post-processing such as CNC milling machines, ovens, and other equipment are usually unavailable on board.

The top level, Level 4, is characterized by a significantly higher level of complexity. Here, an integrated and final quality assurance process is possibly needed to produce certified components. Furthermore, small series production for general use and introduction in the military is also possible.

2.0 ANALYTICAL METHODS

In contrast to the work of Rinaldi et al., Khajavi et al. and Westerweel [5]–[7] the focus of this work is on temporarily self-sufficient systems such as ships. The key element, similar to Westerweel, is the mapping of supply periods in which the system can be supplied. In addition, the use of additive manufacturing is simulated within different organisational levels. Like Rinaldi et al., a network can be built up in this way. However, this is not built up from different OEMs, but from structural elements within the German Navy. Costs are not considered within the model. The situational failure of system components that lead to a system failure, which in turn affects the overall system, requires prompt repair. This is prioritised much higher than the obligatory spare parts costs. The resulting costs are therefore disproportionate to the failure or partial failure of the entire system. The work is therefore certainly focused on meeting the needs in a timely manner. This should take place as near as possible to the demand side. The goal is contrary to the available resources. The discrete event simulation is intended to provide a first insight into a possible additive manufacturing network that will support the existing supply system in the future.

To investigate the influence of various input variables for the logistical processes supporting ships and boats at sea together with the levels of additive manufacturing, a discrete event simulation was set up in the *MATLAB Simulink* environment. For this purpose, the first corvette squadron of the German Navy was mapped based on realistic data. Through the stepwise integration of additive manufacturing according to the scheme of the pyramid shown in Figure 1, the influence of each level on the following target variables has been shown:

- Average waiting time,
- Open requisitions,
- Cancelled requisitions,
- Controlled disposition (cannibalization) and
- Long-runners (requisitions with expected delivery longer than six months).

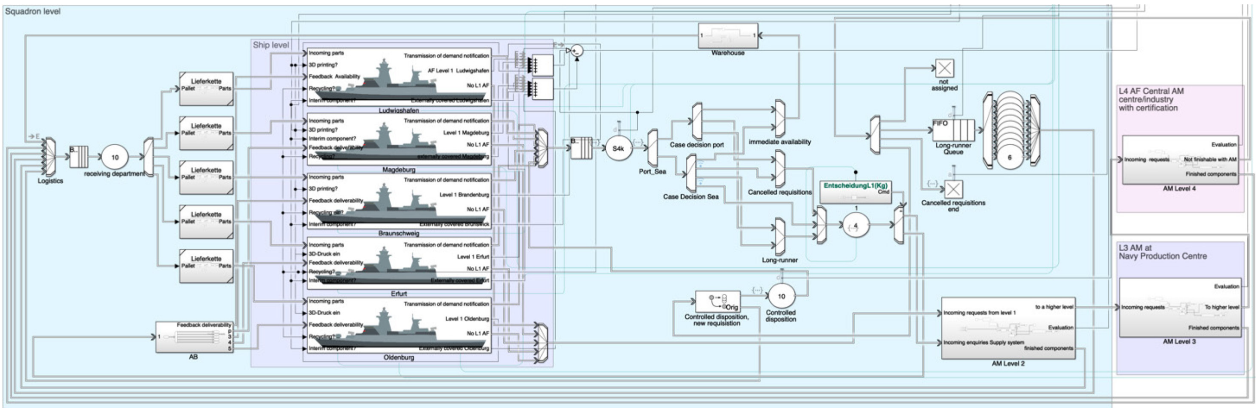

Figure 2: Overview of the discrete event simulation of the German Navy corvette squadron.

On this basis, sensitivity analyses were carried out for all constellations of the integration of additive manufacturing. An overview of the experimental environment is shown in Figure 2. The simulation is divided into four areas. The ship level contains the five corvettes. Within this, the demand for spare parts is created and, if necessary, also met with active additive manufacturing Level 1. This is followed by the squadron level. Here, the requisitions are processed. Additive manufacturing is possible with Level 2 processes here. To simplify the simulation, the bureaucratic parts for processing the requisition in the higher-level systems such as the operational flotilla were omitted. Only the additive manufacturing components Level 3 and 4 were integrated. The individual additive manufacturing components can be used individually and in combination in the simulation, so that the respective influence can be analyzed individually.

3.0 RESULTS

The Discrete Event Simulation was used to identify correlations between input and output variables depending on the different integration configurations of additive manufacturing. These show plausible correlations such as the proportional effect of the transport time and time to dispatch on the average waiting time in the temporarily self-sufficient system. The highest level of additive manufacturing in each case represents the complexity limit up to which use cases can be implemented based on their requirements. If the competence of the operator and the possibilities of the machine increase, the complexity of the level increases. Higher levels of complexity can reduce the number of cancelled requests, controlled dispositions, and long-runners. However, it also becomes apparent that as the level of complexity on board increases, more components are produced and this increased use results in waiting times for conversion, so that the number of open demand notifications increases and thus also the average waiting time. Input variables such as post-processing, data preparation and set-up time play a subordinate role in the overall context of the processing of use cases regarding the average waiting time.

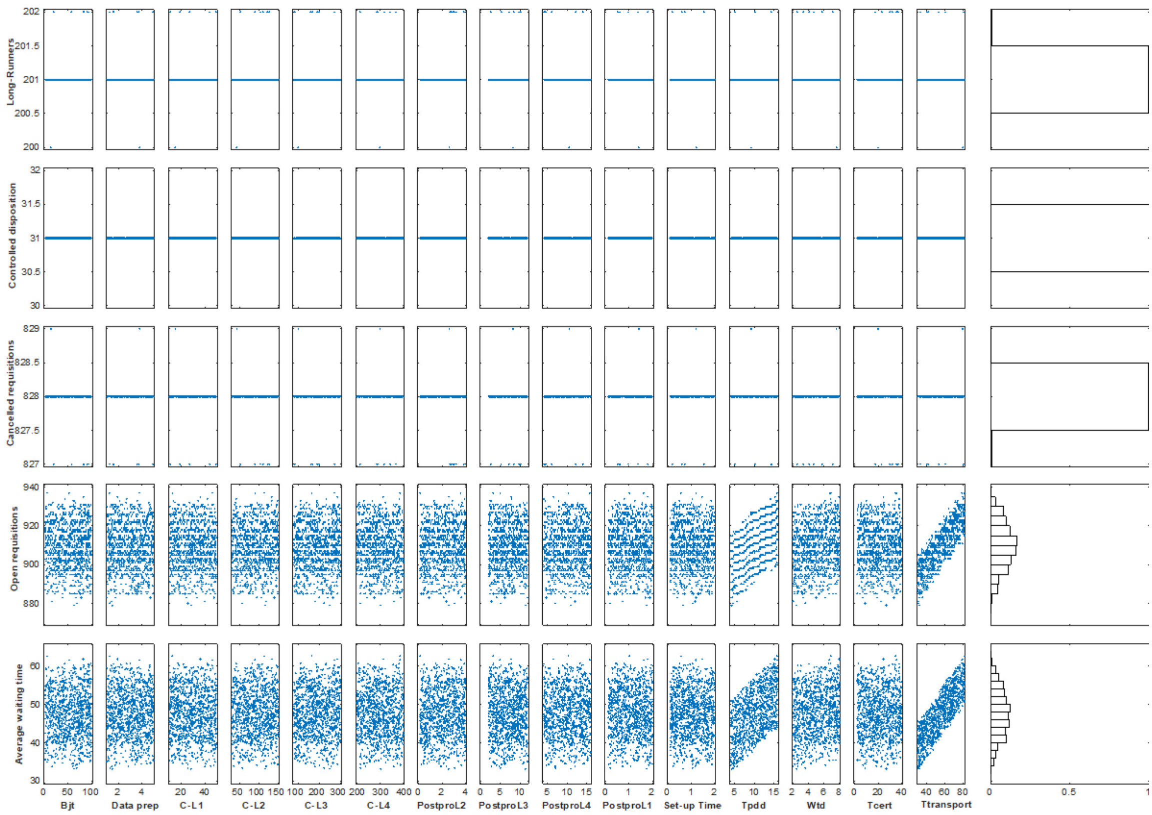

Figure 3: Result of the sensitivity analysis without additive manufacturing.

Figure 3 shows the sensitivity analysis of the baseline condition of the German corvette squadron without additive manufacturing. An explanation of the abbreviations used within the DES simulation is shown in Table 1. There are no improvements in the target variables, this corresponds to the expectations. The number of open demand notifications as well as the average waiting time vary according to the input variables. There is a proportional correlation between the time from processing the delivery to dispatch and time for transportation with average waiting time and open requisitions. The use of additive manufacturing Level 1 is shown in the results of the sensitivity analysis in Figure 4. Here, the clear influence of the possible fulfilment of demand on board is evident. Depending on the level of complexity of the additive manufacturing component on board, more complex parts can be developed. The number of long-runners, cancelled requisitions and controlled dispositions can therefore be reduced.

Figure 4: Result of the sensitivity analysis with additive manufacturing on board L1.

Subsequently, five experiments were conducted using Level 1 equipment on board boats and ships. Use cases for additive manufacturing were developed with the help of experts. The final experiment was conducted on board a German frigate. Due to the larger space available in the on-board helicopter hangar, a level 2 printer could be integrated. This was not possible in the previous experiments. As a result of including Level 2 equipment, it was possible to manufacture larger components and use higher-strength materials, which increased the range of applications. In the experiment, a *Fortus 450MC* was used as a Level 2 representative and a *Prusa i3MK3S+* and *Prusa Mini* each as a Level 1 representative. The applications and their requirements were documented in tabular form for further evaluation and remained on board for further use and evaluation.

Across all experiments, 153 use cases for additive manufacturing were developed. These included 91 new components, 16 controlled disposition, eleven long-runners and seven cancelled requests. Most of the use cases could be produced with Level 1 devices. Only 13 components required a Level 2 machine and two use cases required Level 3 machines. If the machine was not available on board, the components were manufactured ashore(reach back) and delivered to the next port. An example of a use case is shown in Figure 3. This is a retaining ring for the track ball of an input device belonging to a console used in the operational area of the frigate. The problem here was that the hooks used for the locking mechanism of the original part were broken. A replacement part could not be supplied as an individual part. The complete input unit had to be replaced, which has a total value of approximately 6000€. Additive manufacturing made it possible to produce an interim component so that the device could be used without any restrictions for the operator. During the experiment with Level 1 and 2 devices on board, the interim component was manufactured using both devices and their use on board was tested. Figure 5 shows in black the interim component printed with a Level 1 printer, which can only produce a component with one material. On the right, in red and white, is the version printed with a Level 2 printer, which uses construction material and support material. This support material can be easily mechanically removed in part and can also be washed out using peripheral equipment. Due to the filigree structure, using a Level 2 device proved to be easier to post-process. In the case of the part printed by the Level 1 device, the interim component was damaged when the support structure was mechanically removed.

Figure 5: Retaining ring for trackball from a console input device in the operational section of the ship.

For this reason, all other components were manufactured using a Level 2 manufacturing process. The component was then tested by the frigate’s electronics personnel and used on board once it had been approved. The finished component in use is shown in Figure 6. For the time being, the red color serves to indicate that this is not an original component. In the future, after approval for deployment as a spare part by the Bundesamt für Ausrüstung, Informationstechnik und Nutzung der Bundeswehr (Federal Office of Bundeswehr Equipment, Information Technology, and In-Service Support), matching colors may also be used.

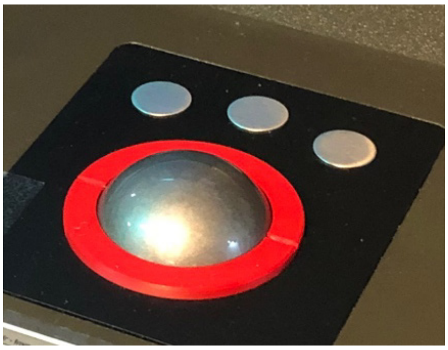

Figure 6: Built-in retaining ring for the trackball in use.

4.0 CONCLUSION

The experiments conducted on board ships and boats of the German Navy with additive manufacturing equipment were able to show which possibilities can be met regarding challenges such as spare parts bottlenecks and the unavailability of materials. By means of a structured implementation based on the presented scheme, a classification can be made so that a simpler categorization can be realized out of the multitude of possible additive manufacturing processes, so that an integration can be implemented more easily. Based on the very successful experiments, the foundation for the implementation of additive manufacturing in the German navy is now planned. Based on the experience gained, a start will be made with Level 1 systems. Due to the lower resource requirements compared to the integration of level 2 systems, a wider range of ships and boats of the German Navy can be covered. These will be integrated in a step-by-step integration so that an evaluation can be conducted between the integration steps. Subsequently, a nationwide implementation of Level 1 equipment is planned. Building on this basic capability, Level 2 devices will then be deployed where the greatest possible benefits are anticipated. It is to be expected that the demand and the complexity of the use cases will increase with the increasing degree of integration, the empowerment of the personnel and the knowledge of the future users, and thus the use of higher-level devices will also increase. Based on Discrete Event Simulation, attention must be paid here to ensure that the personnel on board are not overwhelmed, as otherwise there will be a bottleneck in the process.

A promising approach for introducing additive manufacturing in companies or organizations is the feasibility analysis by means of definite demonstrator components [8]. In this way, potentials, opportunities, limitations, and risks can be assessed based on technological, economic, ecological, and legal aspects in an exemplary and optimally transferable way to further applications. This approach does not necessarily have to be associated with the acquisition of owned 3D printing machinery, equipment, and the associated peripherals. Initially, cooperation with established companies, institutes and networks is also expedient. In this way, employees can be introduced to the new technology, initial applications can be analyzed extensively and strategic decisions on the introduction of additive manufacturing can be prepared based on this experience. This still leaves the make or buy decision open, which depends on factors such as available human resources, qualification level of the employees, possible component spectrum in terms of number and variety, product as well as production cost structure, risk shifting and logistical concept.

A concrete application-driven maturity analysis and demonstrator approach for the introduction of additive manufacturing has been implemented in the German Armed Forces. From the beginning, the entire process chain, from component selection to approval of the components for operation, was analyzed considering technical, economic, ecological, logistical, legal and approval aspects. [5]

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7.0 ANNEX

Table 1: Explanation of the abbreviations used within the DES simulation.

Bjt	Build job time
Data prep	Data(model) preparation
C-LX	Complexity AM Level X
PostproLX	Post processing Level X
Set-up Time	Set-up time for AM machine
Tpdd	Time from processing the delivery to dispatch
Wtd	Waiting time till dispatch
Tcert	Time for part certification
Ttransport	Time for transportation