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Risk Assessment in the Selection of Parts for Additive Manufacturing

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Abstract

The article deals with the analysis, assessment and determination of risk associated with the implementation of repairs to the maintenance system after a breakdown of a military wheeled vehicle. During the temporary repair, we assume the replacement of failed parts with spare parts, whose were produced by additive manufacturing process. The article describes a possible approach to the categorization of individual parts of an integrated system (military wheeled vehicle) in terms of their manufacturability using additive manufacturing technologies, especially Fused Filament Fabrication (FFF) technology, assuming the use of all currently available production materials. In case that these technologies are integrated into the logistics chain to ensure preventive or corrective maintenance of equipment, it is theoretically possible to shorten the period of unusable state caused by logistical delays while maintaining the reliability of the equipment. For the purposes of risk analysis for a wheeled vehicle, the analysis method was chosen: Failure Modes and Effects Analysis (FMEA).

KEY WORDS: *temporary repair, military equipment, additive manufacturing, fused filament fabrication, failure modes and effects analysis, risk treatment*

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1. Introduction

Contemporary technology of additive manufacturing in the machine industry makes it possible to produce products from various materials. At present, spare parts from elastomers, plastics, and thermoplastics can be produced using the mentioned technology. The technology of production of stainless steels, aluminum alloys, titanium and high-strength steels is already developed and used [1- 4].

Potential metal products by "Powder bed fusion" and "Direct energy deposition" technologies currently reach maximum dimensions of 300x400x500 mm [5]. Thus, a significant part of the total number of components of a military wheeled vehicle can be produced with these technologies. Of course, the mentioned technology cannot be used on the load-bearing parts of frames, body parts, parts of basic and additional armor protection, drive shafts transmitting the torque between the gearbox, additional gearbox and subsequently to the distribution boxes of individual axles and many other large parts. Using current technology, it is also not possible to produce vehicle suspension elements such as the standard cylindrical coil springs or torsion bars due to the absence of the required internal structure of the material, i.e. the required shape and orientation of the grains. It is still not possible to produce components made of more diverse material, i.e. crystalline material, typically metal and amorphous material. For vehicles, it is rubber that is vulcanized to metal.

In the area of production of products made of plastics, thermoplastics and elastomers, components up to dimensions of 914x609x914 mm can be normally produced [6]. The resulting maximum dimensions of the products will also cover a significant part of the components of military wheeled vehicles made of plastics, rubber and elastomers. The production technology cannot yet produce shaft seals, hoses and belts with a metal or cloth cord.

2. Default Conditions and Risk Assessment Analysis Methods

The full combat capability of military vehicle can be described as the maintenance of four basic functions, which include - mobility, functionality of the fire system (in case of combat vehicle), protection of the crew and also communication. A fundamental condition applies to military equipment as such, which is to maintain the operability of a military vehicle in combat (emergency) conditions, which means ensuring the tactical mobility of military vehicles even at the cost of using temporary repairs.

For purposes of determining the risks of manufacturing spare parts using additive manufacturing, the aspect of complexity of subsequent mechanical processing of the functional surfaces of the components to the nominal size and roughness of the surface was not taken into account. Also, the need for subsequent heat treatment of the components, which would be necessary especially in the case of metal components, in terms of achieving the required mechanical properties of the material (tensile strength, hardness, resistance to dynamic fatigue stress), was also not taken into account. From the point of view of the risk assessment of the use of additive manufacturing, it was possible to simplify, because we assume the use of a temporary repair, which is a physical intervention that allows the object that is in a faulty state to perform its required function for a limited time, until it is possible to carry out the repair [7].

For the temporary repairs purposes, the components of the systems ensuring the function of the engine and vehicle drive were analyzed in terms of the greatest influence on the mobility of military wheeled equipment.

For the purposes of risk analysis, failure modes and effects analysis (FMEA) [8] was used, which is commonly used in machine design in combination with the fault tree analysis (FTA) method.

3. Risk Analysis of Spare Parts Produced by Additive Technologies

3.1. Identification of risks of failures of manufactured spare parts

For the purposes of the subsequent analysis, the following categories of threats were identified that may arise in the event of a failure of a spare part produced by additive technology in terms of their consequences and the likelihood of the threat being realized. For the purposes of the analysis, a failure is meant to be a structural failure of components. For analysis purposes, the following severities of consequence S were identified:

I. The operability of the vehicle's powertrain is maintained to its full extent even after a component failure. It is possible to repair or replace a component that is in a failure state as part of the following planned preventive maintenance, or as a condition-based repair after complete disassembly of units and devices. Possible reduction in comfort and ergonomics of vehicle control. Value (1 – 2 according to severity).

II. The operability of the powertrain is partially reduced, but all functions of the vehicle's powertrain are preserved. There is an increased consumption of fuel or operating fluids. However, it is possible to compensate for excess consumption of operating fluids after stopping the vehicle after completing the task, or as part of regular inspections. It is assumed that the task will be completed with a maximum mileage in units of hundreds of kilometers. There is an increased transmission of vibrations of the powertrain to the ladder frame chassis of the vehicle and subsequently to the cabin of the crew. Increased powertrain noise. However, it is possible to continue operating the vehicle with respect to the need to increase maintenance requirements after use in terms of the time needed to perform it and the consumption of operating fluids and fuels beyond the defined norm. The ergonomics of vehicle control may also be affected by damage to the control elements of the powertrain. Value (3 – 4 according to severity).

III. The operability of the powertrain is greatly reduced and some functions of the powertrain are not preserved. This is the so-called safe mode, when the vehicle's electronic control unit intervenes and disables some functions, as an example it is possible to name: reduced engine power, impossibility to shift all gears, impossibility to shift reduced gears, impossibility to use the drive of both axles, impossibility to operate differential locker. However, it is possible to continue operating the vehicle without causing secondary damage to other components and units that were operable when the fault occurred. On the vehicle, it is necessary to perform a routine repair consisting of replacing or repairing the given component immediately after the task has been completed. Value (5 – 6 according to severity).

IV. The operability of the powertrain is greatly limited, in the order of units to low tens of kilometers, secondary irreversible damage to components and units would occur and, subsequently, to the complete inoperability of the vehicle. These are leakage of mechanical devices and the associated massive leaks of operating fluids, a complete leak in the overpressure part of the air supply system to the engine (overrunning of the turbocharger above the level of maximum operating revolutions). However, it is possible to leave the danger zone with the vehicle and then regroup the crew of the vehicles, transfer the payload and equipment. Value (7 – 8 according to severity).

V. The vehicle is inoperable immediately after the failure. The transmission of torque to the vehicle wheels will be interrupted. The vehicle must then be destroyed and abandoned, or it must be removed using an adequate recovery means. Value (9 – 10 according to severity).

3.2. Evaluation of the probability of failure of the manufactured spare part

Due to the fact that in the case of FFF technology, it is a relatively new production technology for providing a whole range of components from different materials that are suitable for different component shapes and their loads, it is therefore not possible to clearly determine discrete values of the probability of occurrence of a failure for spare parts for military wheeled equipment produced in this way, or intervals of values based on reliability and lifetime of products testing. Currently, these are prototype spare parts for which there is no failure intensity database or data on their failures that could be statistically evaluated. For the purposes of the analysis, the authors therefore proceeded to a qualitative assessment of the occurrence of failure based on the complexity of the topology of the part and the associated high probability of occurrence of internal structure failures of the material. Due to the complex production procedure (scan strategy) and the associated supercritical cooling rate of the material and the subsequent emergence of residual stress and the chosen production technology, delaminations and porosity occur [9 -12]. Another variable that negatively affects the probability of failure is the amount of force or thermal stress on the component.

For the purposes of analysis, the probability of occurrence of a failure is categorized O due to the complexity of the geometry (topology complexity) of the component, the following:

I. simple thick-walled geometry (1 – 2.5);
II. indented thick-walled geometry (2.5 – 5);
III. simple thin-walled geometry (5 – 7.5);
IV. complex thin-walled geometry (shell, lattice structure) (7.5 – 10).
V.
VI. The magnitude of the load on the component also affects the probability of failure, which can be categorized for analysis purposes as follows:

ad I) The component is loaded in one direction with a slight force, small torque, low (atmospheric pressure), atmospheric temperature (e.g. flexible line holders, wiring, components of the engine air supply system - low pressure part, engine filter housing, control levers, boxes for electronic control units, fuse box, battery cover) (1 – 2.5 depending on the size of the load).

ad II) The component is loaded with a compound stress of small force, small torque, low (atmospheric pressure), increased temperature in the engine-transmission compartment (e.g. holders of individual components of groups, power steering pump holder, air compressor holder, air dryer holders) (2.5 – 5 depending on the size of the load).

ad III) The component is loaded with higher force, torque, medium pressure (250 – 760 kPa), medium temperature (approx. 100 – 200 °C), (e.g. engine air supply line - high pressure part, power steering hydraulic fluid line components, components of compressed air brake system, components of the cooling system piping, pipeage of engine oil and hydraulic fluid of the hydrodynamic converter and automatic transmission, components of propulsion of auxiliary aggregates from the engine - components of the hydraulic pump, compressor, oil pump, engine starter, components loaded by the weight of individual units) (5 – 7 .5 depending on the size of the load).

ad IV) Components are loaded with maximum force, torque, maximum pressure (up to 200 MPa), or high temperature (approx. 200 – 1,000 °C). Examples can be components of the high-pressure circuit of the fuel system, components of the exhaust system in front of the oxidation filter, components of the powertrain loaded with the maximum torque of the engine, components loaded with the weight of the vehicle (7.5 – 10 depending on the size of the load).

3.3. Categorization of the difficulty of fault detection

Component fault detection D is categorized into the following groups for analysis purposes:

I. A very high level of component failure detection capability. The malfunction can be detected, for example, by the lighting of a warning light on the driver's dashboard (MIL warning light, lubrication warning light, pressure drop on brake circuit pressure gauges). By switching the vehicle to safe mode. Detectable by hearing (value 1 – 2).
II. High level of fault detection capability. The malfunction is evident when checking the vehicle as part of the pre-departure inspection or as part of the inspection at the stops. Especially obvious leaks of operating fluids (value 3 – 4).
III. Medium level of fault detection capability. The fault is detectable during basic vehicle maintenance. This is the detection of leakage of operating fluids during the optical inspection of gauges and leveling tanks (value 5 - 6).
IV. Low detection level. The fault can be detected optically when disassembling devices and components from the vehicle (value 7 – 8).
V. The fault is not detectable at the given maintenance level (value 3 – 4).

4. Risk Assessment

4.1. Description of the risk assessment

A total of 878 individual parts of the powertrain were analyzed, while 226 items were assessed as viable for replacement with a part manufactured using additive technology. Among the reasons why in specific cases it is not possible or advantageous to approach this method is another production technology, these are electrical or electronic components, parts created by a specific technology (vulcanization, parts with functional coatings, etc.), parts made of specific functional materials (sliding bearings, rolled sheet metal parts, springs, etc.) and large parts that cannot be segmented for production purposes (die cast housing of units, forgings, sheet metal bending and forming parts) (fig. 1).

For understandable reasons, standardized components (screws, nuts, washers, rivets, locking tongues, bearings, etc.) were excluded from the analysis, due to their great interchangeability and good availability. Their piece production with this technology has no relevant justification.

For the purposes of evaluating risks analyzed by the FMEA tool, the evaluation of the degree of risk, the risk priority number, is used. Based on the combination of the probability of the occurrence of the risk and the seriousness of its consequences, it is possible to determine the degree of risk. In this case, the numerical expression of the risk can be:

$$R = S \cdot P \tag{1}$$

where R – numerical value of the risk, S – the severity of the consequences of the failure and P – the probability of occurrence of the failure [13].

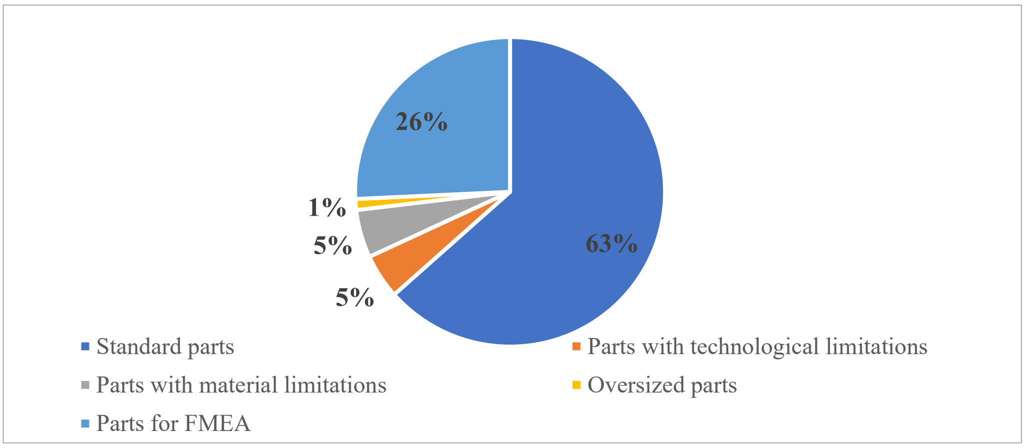

Fig.1. The share of evaluated parts of the powertrain of a military wheeled vehicle in terms of manufacturability using FFF technology [own].

Table 1.
Criticality matrix of individual parts of the powertrain produced by FFF technology – part A

Likehood	**Very high**				
	High		Screen, covering - (exhaust system)		
				Fibre packing - (turbocharger) Spring tube - (engine block) Spring tube - (engine block)	Set rings - (crank mechanism) Fibre packing - (crank mechanism) Coupling - (lubrication system)
	Medium	Holder - (fuel supply system)	Thermoregulator gasket - (cooling system) Thermoregulator gasket - (cooling system) O–ring (non-standard) - (Cooling system) Fibre packing - (valve cover)	Fibre packing - (turbocharger, oil lubrication) Gasket - (cooling system, lubrication system) Asbestos, copper sealing - (air intake system) Fibre packing - (cooling system)	Intake bent tube - (air intake system) Bush, insert - (turbocharger) Plastic tube - (air intake system) Plastic tube - (cooling system)
		Suction tube holder - (engine block) Filling tube - (lubrication system) Holder - (fuel supply system)	Filter holder - (fuel supply system) Fibre packing - (lubrication system) Bush, insert - (fuel supply system)	Cover ECM - (engine electronics) Special screw - (engine block) Gasket - (lubrication system) Stop gasket - (lubrication system) Plug - (valve cover)	Manifold to engine - (air intake system) Gasket holder - (engine block) Fibre packing - (air intake system)
	Low	Tube gasket - (lubrication system) Filler cap - (lubrication system) Neck - (Crank mechanism) Cover, lid - (drive belt) Holder - (fuel supply system)	Oil T–filling tube - (lubrication system) Coupling - (electrical system)	Gasket holder - (cooling system)	Neck - (engine block) Nozzle - (lubrication system)
		End piece - (lubrication system) Special coupling (Fuel supply system)	Plug - (lubrication system) Protection, protector - (electrical system)	Bent tube turbo - (turbocharger) Blind plate - (engine block)	
	Very low	Neck holder - (lubrication system) Serrated split pin - (crank mechanism)		Coupling - (air intake system)	Bent tube - (engine)
		Operable without limitations		**Partial reduction of operability**	
		Consequence, risk impact on operability			

Table 2.
Criticality matrix of individual parts of the powertrain produced by FFF technology – part B

Likehood	Very high						
	High			Exchanger, set of tube - (lubrication system)			Cooling tube EECU of engine - (fuel supply)
		Return pipe - (lubrication system)		Holder, LH - (engine) Holder, RH - (engine) Coupling - (thermostat) Screw H c/w shoulder - (cooling system) Cylinder head cover - (engine head)	Return pipe - (turbocharger) Flow screw - (turbocharger)	Flow screw - (fuel supply system) Coupling - (air intake)	
	Medium	Filter cover - (lubrication system) Stop gasket - (lubrication system) Tube, manifold - (air intake system)	Plug - (engine block) Collector - (exhaust system) Gasket - (fuel supply system) Rubber connection - (fuel supply system)	Holder LD CCF - (engine) Holder PD CCF - (engine) Plug - (engine block) Cooler - (lubrication system) Coupling - (cooling system)	Oil pump - (lubrication system) Thermostat body - (cooling system) Plug -(cooling system)	Wrench pin - (crank mechanism) Coupling - (air intake system)	Piston–rod; Crankshaft - (crank mechanism)
		Rear engine bracket, LH - (engine block) Rear engine bracket, RH - (engine block)	Bush, insert - (engine block) Plug - (oil filter) Stop gasket - (oil filter) Plug - (cooling system)	Flange set - (crank mechanism) Tensing puley - (drive belt) Alternator bracket - (electrical system) Plug - (lubrication system)	Tube, manifold - (cooling system) Bent tube - (cooling system)	Sieve oil - (oil pump)	
	Low	Air wing - (cooling system)	Steel line - (cooling system)	Front bracket, LH - (engine block) Front bracket, RH - (engine block) Tube, manifold - (Lubrication system)	Plug - (engine block) Plug - (engine block) Plug - (engine block)	Pulley - (drive belt)	Special coupling - (fuel supply system)
		Plug - (cooling system)		Neck - (engine block)			
	Very low	Fan carrier - (cooling system)					
		Significant reduction of operability		**Operability is severely limited (very limited range, possibility of secondary damage)**		**Loss of operability**	
		Consequence, risk impact on operability					

Subsequently, it is possible to proceed to the creation of a criticality matrix as a result of the failure (table 1, 2), on the basis of which it is possible to determine the acceptability of the risk and thus, in this particular case, to select specific parts for which their replacement with a part produced by FFF technology is acceptable in terms of criticality. While the acceptable rate is set differently for various areas. In technical applications, as a rule, we do not want to accept the loss of system operability due to a failure with a very high probability of failure. This statement essentially sets a maximum numerical value of risk of $R = 100$.

Parts for which the risk value reaches R=20 are replaceable without serious consequences for the reliability of the system (marked in green in table 1 and table 2 (left part)). The parts that are marked in red in the tables (right part) cannot be replaced under any circumstances, and the replaceability of the parts in the yellow field must be assessed subsequently case by case.

The risk priority number is subsequently used to determine the priority when focusing on mitigating failure modes caused by component failure, whose risk value lies precisely in the interval $R = (20, 40)$, i.e. in the yellow area (middle part) of table 1. The risk priority number (RPN) is determined by calculating [13]:

$$RPN = S \cdot O \cdot D \tag{2}$$

where O – the probability of the occurrence of a type of failure or the class number of the failure mode, D – classifies the failure detection coefficient, i.e. estimates the hope that the failure will be detected, S – the severity of the consequences of failures.

Due to the fact that the risk index R and the risk priority number is the product of the probability of the realization of the threat O, respectively the probability of the occurrence of a failure, the severity of the consequence S and in the second case in addition coefficient of the difficulty of detecting the given type of failure D. Also, on the basis of the performed categorization of the probability of the realization of the threat, two parameters enter the evaluation. One on the side of the product, the other on the side of load distribution, and the influence ratio between these parameters cannot be clearly defined for all parts. For reasons of maintaining proportionality to other coefficients, the category of the probability of failure is therefore determined as the average value of the coefficient due to the complexity of the geometry of the part and the size of the load of the part.

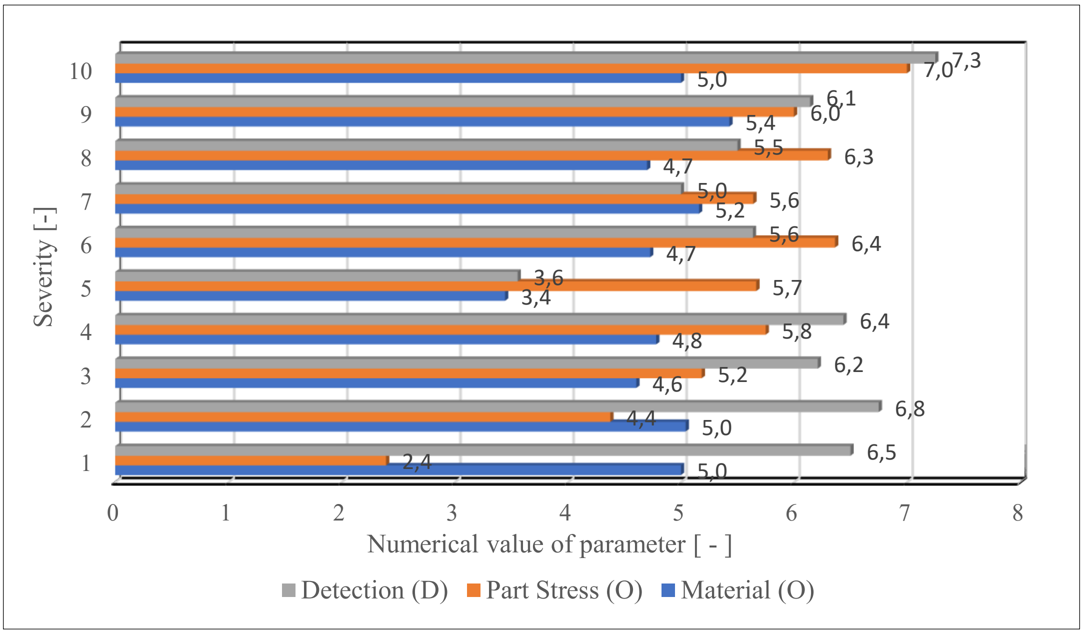

Fig. 2. The graphical interpretation of the relationship between the severity of the consequences of the failure and the other assessed parameters

In the case of failure modes with similar or identical *RPN*, it is necessary to focus attention on those failure modes that have higher value of severity of consequences of failure *S*. From the last graph (fig. 2), the average values of the assessed parameters show the relationship between the severity of the consequences of the failure *S* and the other assessed parameters *O*, *D* [13]. The graph clearly shows a predictable trend, i.e. that together with the increasing stress on the components, be it mechanical, thermal or other, the severity of the consequences of the failure also increases. What may seem surprising, however, is the fact that for components with the highest severity of failure consequences, the value of the failure detection difficulty coefficient reaches the highest values. This is in fundamental contradiction to the basic assumption of the creation of any system, namely that the failure of critical elements from the point of view of system reliability should be the most detectable.

4.2. Risk Treatment is the process of selecting and implementing measures to modify risk

For the area of temporary repairs, we can afford an exceptional procedure consisting in the removal of the source of risk. In practice, this means that for components above the maximum acceptable level of risk, we will not allow a temporary repair by replacing the component with a manufactured spare part. In the event of a failure of a part, the replacement of which in terms of the probability of occurrence of the failure, the severity of the consequences and the level of detectability lies in the area of unacceptable risk, the only alternative is the installation of an approved spare part that meets ISO 9001. In order to restore the operability of the technology, it is therefore necessary to carry out a routine repair in accordance with technological procedures for repairs, regardless of the current availability of a spare part. A temporary repair in the event of a malfunction of such a part does not affect the indicator of maintainability and assurance of maintenance of this technology.

5. Conclusion

Through analysis and risk assessment, specific spare parts from the vehicle powertrain were selected as part of this work. These could be replaced in the event of failure using unapproved spare parts produced by additive manufacturing processes within the temporary repair system designated for military ground equipment. Thus, the risk assessment determined the optimal acceptable risk level of the application of the system of temporary repairs to the corrective maintenance system of the vehicle in specific combat conditions. By the risk treatment, specific spare parts were specified, the replacement of which in the described sense does not have a significant effect on the inherent reliability of the system, in this case the military truck, from the point of view of failure. At the same time, the maintainability and maintenance assurance is improved in the sense of shortening the maintenance time after a failure and logistical delay, especially in the case of deploying technology in foreign operations, where logistical support is more complicated.

For the effective integration of temporary repairs into the corrective maintenance system, the risk assessment and determination of specific parts that may be subject to the system of temporary repairs must be followed by further analyses, in particular the analysis of the manufacturability of the part under the given conditions and the evaluation of production costs.

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