

## RATIONAL DECISION-MAKING FOR THE BENEFICIAL APPLICATION OF ADDITIVE MANUFACTURING

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### Abstract

Additive Manufacturing is a technology that offers a high potential for industrial companies. Nevertheless, companies lack experience with this new technology and face the problem to identify processes where a successful and beneficial application can be achieved. They have to be supported in this analysis with a decision support tool which is capable to compare different manufacturing or repair approaches in order to determine the optimal solution for the correspondent use case. This is not always driven solely by costs but can also be critically affected by further influencing factors. This is why the decision support takes into account also time and quality alongside the costs. For a time-critical spare part supply, for example within aerospace sector, they are substantial for taking a decision. The presented decision support features a multi-attribute decision-making approach for selecting the most appropriate process, either Additive Manufacturing, conventional technologies or an external procurement.

**Keywords:** *Additive Manufacturing, Decision Support, Aerospace, Spare Parts, MADM, Multi Attribute Decision Making*

### Introduction

Additive Manufacturing (AM) is a technology that uses a layerwise production of parts. The shortfall of tools allows for several different potentials such as the production of complex parts with nearly no extra costs or a high flexibility as there are only low setup costs. By this, also low unit quantities and single unit production can be realized economically [Geb13]. The specific characteristics also enable the production at the point of use in order to reduce shipping efforts in terms of cost and time. Consequently, a reduction in warehousing is possible [GRS10]. These benefits are favorable for spare part industries exhibiting a high part value and a time critical logistic [HPT+10]. An example for such an industry is the aerospace spare part business. The aerospace sector is characterized by a high competition also driven by the low cost carrier. This forces the airlines to increase the availability of their fleet and to minimize downtime of their aircrafts caused by defects [Pri11; Bau02]. Thus, it is necessary to thoroughly maintain the aircrafts in order to keep them in an airworthy state. Besides costs for fuel, the maintenance of aircrafts is the second largest cost driver for an airline [Men13]. Therefore, Maintenance, Repair and Overhaul (MRO) providers are an important partner for the airlines but also need to work cost-efficient to stay competitive. This requires the constant improvement of their processes, one opportunity being the application of new technological approaches to repair or produce parts. AM is such a technology and the potentials stated above can generate a benefit within the workflow. But the companies lack experience with this new technology which is presently not integrated into current processes [DK14]. This is why a methodology and tool is required that supports the decision

whether it is economically reasonable to apply the technology for a certain repair or production case. A multitude of economic and technological aspects have to be considered within the adoption of AM. At the same time the high safety standards of the aerospace industry have to be met and a high product quality has to be achieved [Paw16]. All in all, the major influence factors which need to be taken into account simultaneously are time, quality and costs for determining the decision which technology needs to be applied. This can lead to a complex net of involved factors which is often problematic in decision making when there are no tools available to support this process [TSD14]. Therefore, a decision support is required that helps companies to choose the most cost-efficient technology for a certain use case.

### **Aerospace Industry**

The aerospace sector is characterized by a high investment volume for the aircrafts and an intense competition, which necessitates the maximization of the aircraft's operation time to generate earnings [Pri11]. Therefore, the thorough maintenance of aircrafts is inevitable as there are rigid rules by the authorities to guarantee the safety of the aircrafts [FL09; Hin10]. Nevertheless, the complex system of an aircraft, the high requirements and environmental impacts during the operation lead to unexpected defects and component breakdowns [Men12]. This requires a fast and effective repair and replacement so that a complex logistic network is mandatory. The conventional productions systems are not fast and flexible enough to respond to this short-term demand so that extensive warehousing is conducted in this sector. Additionally, aircrafts exhibit a long product life-cycle with 10 years development, 20 to 40 years market availability and an operation phase of up to 25 years, summing up to almost 70 years of the need for spare part availability [SGF08]. The high safety and quality standards combined with often complex part designs lead to high costs of working capital. A study estimates that the value of the worldwide aerospace spare parts is between 20 to 30 billion US-\$. It is further assumed that 22% of this value are the annual costs for storing these spare parts, being about 5 billion US-\$ spent on storing, taxes, insurance, obsolescence and capital expenses per year [FL09]. A reduction of the spare part amount could lead to 'Aircraft on Ground' situations where costs to the amount of more than 100,000 US-\$ can arise per day when an aircraft is not able to further operate [SGF08]. Thus, a fast and flexible, but expensive spare part supply is implemented in aerospace showing the potential for significant cost savings.

When a defect part is detected by the Maintenance, Repair and Overhaul (MRO) service provider it can either repair the existing part, or produce or buy a new part [Men12]. Capabilities and certifications may influence this choice but are not subject for the further analysis of this paper. Besides the 'make-or-buy' approach, the MRO company has to determine which process is the most efficient solution to get to an airworthy part again. This is where a decision support is required.

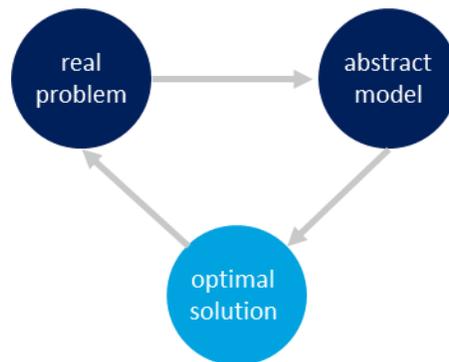
### **Principle of Decision Support**

Events, needs and changing environmental conditions evoke situations where complex decisions have to be made. In this course, influencing parameters and uncertainty have to be processed to get to the optimal solution for the given situation [EWL10; GK06]. Problems can arise from a huge number of action alternatives, fragmented information or dynamic processes. It is then usually the aim to choose the beneficial action alternative to maximize the benefit for a given objective of the decision maker on a rational basis. While a disadvantageous decision can influence the business success in the long run negatively, the selection of a beneficial alternative is substantial for the successful development of a company. Because there is usually subjective preferences involved it is necessary to make this subjectivity transparent and reproducible. [FK08]

The decision theory is divided into two categories. The first one is called descriptive decision theory and deals with the process how decisions are made in reality. Persons are analyzed how they react and their behavior is abstracted so that the results can be used within the second category, called prescriptive decision theory. This involves an analytical process how to take a rational decision. A proceeding to choose the best alternative and solutions to process information are given. The inclusion of the subjectivity is part of this process to determine the optimal solution for the decision maker. [GK06; FK08; BCK12; LGS12; Lau07]

In order to be able to get to this solution, it is necessary to transfer the real problem to an abstract model which eliminates those influence factors which are not essential for the decision making (**Figure 1**). In this course, inaccuracies emerge but are tolerated in order to simplify the reality and make it penetrable [LSR06]. Therefore, the decision problem is divided into its components of action alternatives, consequences, environmental conditions, objectives and preferences of the decision maker. If uncertain conditions exist, probabilities for their occurrence have to be assigned otherwise the degree of certainty can be described as safe. [EWL10]

Decision problems can have a variety of shapes. Consequently, there is also a number of different approaches to deal with the specific characteristics of these decision problems so that some models are better suited for certain situations than others. The selection of a suitable model is therefore an important step in the preparation of a decision support methodology. Factors for this selection are the number of aims, the information quality and the quantity of decision levels which is linked with the complexity of the problem. Higher complexity is existent when multi criteria problems have to be solved. They often consist of quantitative and qualitative criteria which have to be made comparable. [Oss98]



*Figure 1: Abstraction of reality to be able to process the decision problem [LSR06]*

The number of alternatives is also relevant for the classification of the type of problem solving. For a finite number of alternatives which can be clearly described, a discrete solution space is existent and Multi Attribute Decision Making (MADM) is applied. The optimal solution is searched for and a ranking order is created even if different scales and units have to be processed. If an infinite quantity of alternatives have to be dealt with, the solution space is continuous and Multi Objective Decision Making (MODM) methods are applied. That means that the solution space is limited by constraints but not the number of alternatives. A system of equations is used to calculate the solution for the mathematically described objective function.

Figure 2 shows that the problem structure is structured when in every phase an appropriate procedure is available and the decision maker uses it. In contrast to that, unstructured problems have no procedure in any phase. Semi-structured problems are in between these two extreme cases. An allocation to one of the three groups depends on the subjective assessment of the available information quality. [AAB+14; BH95]

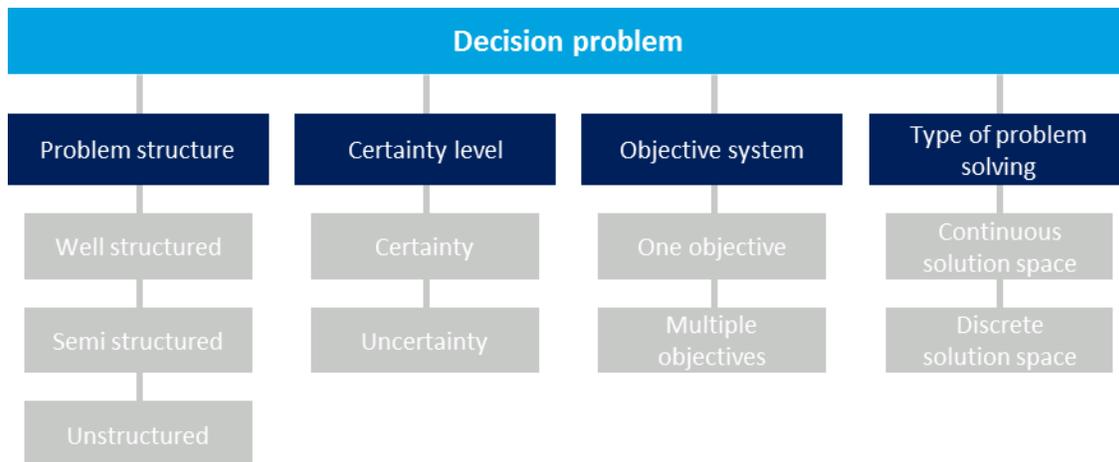


Figure 2: Classification of decision problems

In order to get to a decision support a specified process has to be conducted, shown in Figure 3. This systematic approach enables the transformation of a problem from reality into a solvable model with cause and effect relations [Mau01]. It starts with the problem identification where information of the problem is gathered and the basis for the following steps is provided. Then the problem is classified by structuring its elements, amongst others alternatives, objectives and uncertainties, for the differentiation of the problem. This input is used to establish the actual model where criteria are defined and values are determined. The use of the model identifies the favorable action alternatives and provides a ranking of them. Within this step it is further analyzed whether the model and its data is applied correctly and whether the results are robust. The last phase then suggests a proposal for solution for the given decision problem which should be reflected critically. If an approach for optimization can be identified in any phase, the findings should be integrated into the correspondent phases to achieve more precise results. [BS02; EWL10; Göt08; GL14-ol]

Through the finite number of alternatives that are present in the present use case the MADM methods are suitable for solving the problem. Within this field there are two different approaches. The American approach is based on clear and precise objectives, criteria and weightings. Typical methods are AHP and the utility analysis. The European approach is better suitable for situations where these elements are not that easy to identify and to quantify because the data set is fragmentary. From this, the outranking functions have been derived which are able to identify a favorable alternative even if preferences are not precise and the information inconsistent. The alternatives are compared pairwise in order to generate a preference for one of them. This can either be a strict or weak preference, an indifference or incomparableness. The pairwise comparison provides the information for a ranking of all alternatives. Common methods for this approach are Topsis, Promethee and Electre. [GL14-ol; Wen10]

In the field of the decision support there is a huge choice of methods with different procedures being either advantageous or disadvantageous for the present use case. To provide the basis for the selection of a suitable method, the main characteristics of the relevant methods have to be described.

The utility analysis has the aim to identify the non-monetary overall utility value. Therefore, the alternatives are applied to weighted objectives and assessed. The result is a utility value which determines the best alternative and ranks the others. The simple proceeding and the opportunity to also quantify qualitative criteria makes this method an easy to use and often deployed method. [GL14-ol; Zan70]

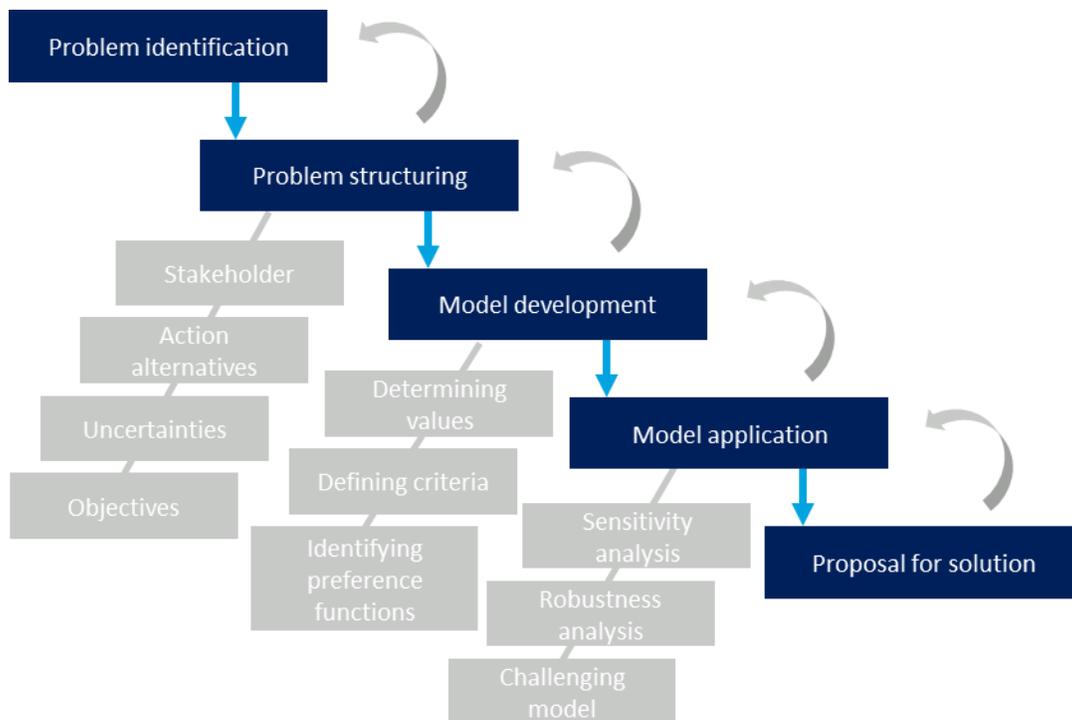


Figure 3: Systematic approach for modelling a decision support [GL14-ol; BS02]

The Analytic Hierarchy Process (AHP) is a method for the structured and systematic assessment of unstructured and inconsistent decision problems. Therefore, relevant factors for the problem are hierarchically positioned and compared pairwise. Depending on the complexity of the problem there have to be levels to a greater or lesser extent in which the factors are grouped. This approach simplifies the comparison for the decision maker for unstructured situations. [Oss98; FDN+08; GL14-ol]

Electre (Elimination Et Choix Traduisant la Réalité) describes a pairwise comparison on the basis of concordance and discordance of the action alternatives. The concordance reflects a value for how much better an alternative is in comparison to another one. The discordance determines the impact for the theoretical case when the alternative would not be better than the other alternative. Thresholds can be defined in order to classify the alternative into indifference, veto and strict preference. [GL14-ol; BS02; Obe10]

The method Promethee (Preference Ranking Organisation Method for Enrichment Evaluations) is also an outranking technique which is able to map incomplete preferences and information. Incomparableness and strict as well as weak preferences can be assigned also based on thresholds. But for Promethee these thresholds can be combined with mathematical preference functions so that different values can be reached. They are called positive preference flow and negative preference flow. They show the strengths and weaknesses of the alternative. In combination with the opportunities of the preference function this enables to rank the alternative lower if it has strengths but also a significant weakness. [Göt08; GL14-ol]

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is based on the approach to determine the Euclidian distance between the alternatives and the best and worst case scenario. Alternatives with a shorter distance to the optimum are favorable. A ranking can be generated on

the basis of their distances. A normalization within the calculation process guarantees that different scales can be used and also qualitative criteria can be applied. [Rao07]

### **Selection of a Decision Support Method**

The selection is a multi-criteria decision problem by itself so that a systematic process shall be applied. They need to be analyzed how far they are suited for the application within the aerospace spare part industry and the determination of the optimal repair or production technique solution. Their advantages and disadvantages are opposed to the requirements and characteristics of the use case. The utility analysis is used for this process as it is simple and often applied. Therefore, the present problem has to be analyzed and classified to identify relevant criteria.

The problem is clear: MRO companies have to work cost-efficient in order to be successful on the market and therefore need to apply new technologies to deploy benefits. AM offers a high potential but companies lack experience with the technology so that economic and successful applications have to be identified. This is complemented by additional criteria from the field of time and quality. The action alternatives and their characteristics are known, the objective is clearly stated so that it can be concluded that the decision situation is semi-structured and the solution space is discrete. The task is to determine the preferences of the decision maker and to derive the consequences and impacts.

The relevant factors that need to be included into the decision support are costs, time and quality. For the costs field the main cost driver are the direct and indirect costs, storage costs and other costs. The time is mainly influenced by the handling time, the shipping time and the production time. The main quality influence factors are part density, accuracy, the surface condition and the overall process stability.

Based on this information an evaluation of the relevant MADM methods needs to be conducted. The utility analysis is easy to use but the weighting can be critical to determine for a higher quantity of criteria. Cost criteria is not intended to be part of the utility analysis. Furthermore, the method makes it possible that high specifications of criteria can compensate a low specification which can lead to a corruption of the suitability of the alternative. Further, an even scale is not for every situation possible but required by this method.

AHP can process qualitative and quantitative criteria and is suited for unstructured problems. It is positive that the decline in information content is relatively low for this method but it is complicated to process a high number of criteria (more than 7) due to complex calculations [FDN+08]. In general, consistency problems can arise for the weighting and a change of the structure and number of criteria is laborious.

Electre can very well handle situations with a limited amount of action alternatives in a certain surrounding. The method only provides a ranking of the alternatives but not a utility value. An advantage over AHP and the utility analysis is a better use of preferences within Electre indicating indifferences and incomparableness. It further enables to limit the dominance of an alternative with a critical value. While the transparency is limited through the concordance and discordance, the method requires only a limited effort.

Promethee is also able to work with quantitative and qualitative criteria, a direct utility value is not compiled, the positive preference flow and negative preference flow indicate the usefulness. They are more transparent in comparison to Electre's values. An important advantage are the preference functions which can be used to further differentiate how big the impact of a certain significance value is incorporated. Additionally, the preparation and execution are uncomplicated.

Topsis is also a method which is easy to use and overall transparent. The normalization enables the use of different scaling which can then be adapted to the criterion's needs. The problem is

fragmented information which is difficult to process with this method. Furthermore, a metric scale is required in order to calculate the Euclidean distance. This is not possible for many criteria which then cannot be included into the decision making process.

The criteria for the selection of a method is based on the key requirements for the decision support methods. They have to be able to map indifferences, shall be flexible and not too complex in its execution. The results shall be definitely and exact while the method shall be transparent. A low data input is favorable while uncertainties shall be able to consider. The methods shall be easy to use to foster the adoption and a software support is preferable to be able to incorporate in and link the methods to the existing IT infrastructure of a company for an integrated software solution also against the background of the factories of the future approach.

The significance value can take a value between 1 and 4. The weighting focuses on the ability to map indifferences, an exact result, convenience and software support. Their according values and the overall results can be found in Figure 4. The analysis has identified the Promethee method as the most favorable approach for the decision support with Topsis being the second most suitable method. Promethee's preference functions have led to high values for the key criteria as they offer the chance to have a very differentiated analysis.

	%	Utility analysis	AHP	ELECTRE	PROMETHEE	TOPSIS
Indifferences	17	1	1	4	4	3
Manageability	9	2	1	3	3	2
Complexity	7	4	3	1	2	3
Accuracy	15	1	2	3	4	3
Transparency	9	3	4	1	3	4
Data input	12	2	2	3	3	2
Feasibility	16	4	3	2	2	3
Software support	15	3	3	4	4	4
<i>Utility value</i>	100	2.38	2.3	2.84	3.24	3.03

Figure 4: Evaluation of different Multi Attribute Decision Making methods

### Development of a Decision Support

The chosen method has to be adapted to the decision problem. Therefore, a profound analysis of the situation has to be conducted in order to identify the characteristics that have to be included in the decision support and which have to be quantified within this process. This is also important for the preference functions of the Promethee method. On their x-axis the difference of two compared alternatives is plotted. The correspondent preference value on the y-axis depends on the preference function that has been chosen. The value can be between zero (indifference) and one (strict preference). Values between these numbers are weak preferences. Consequently, the

threshold values are of big importance and need to be chosen carefully. There are several types of preference functions with different designs and functions [GL14-ol]

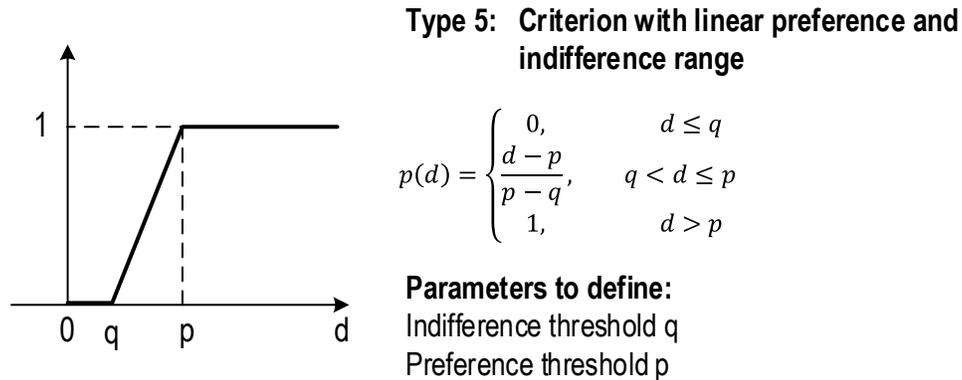


Figure 5: Example for a preference function with different thresholds and the mathematical definition [GL14-ol]

Figure 6 gives an overview of the relevant criteria in order to get to a successful and economic reasonable application of AM. For the costs sector there are direct and indirect provision costs that have to be compared. They are adapted from the sourcing model in accordance with Mensen [Men12]. This is required in order to have the same criteria for all three alternatives, including the acquisition of a new part from the OEM. The fixed and variable costs of the production are assigned to the direct and indirect provision costs. In addition to that, costs for the required space, and storage costs as well as costs that cannot be assigned to one of the groups are compared. All elements can be stated in the same unit, for example US-\$.

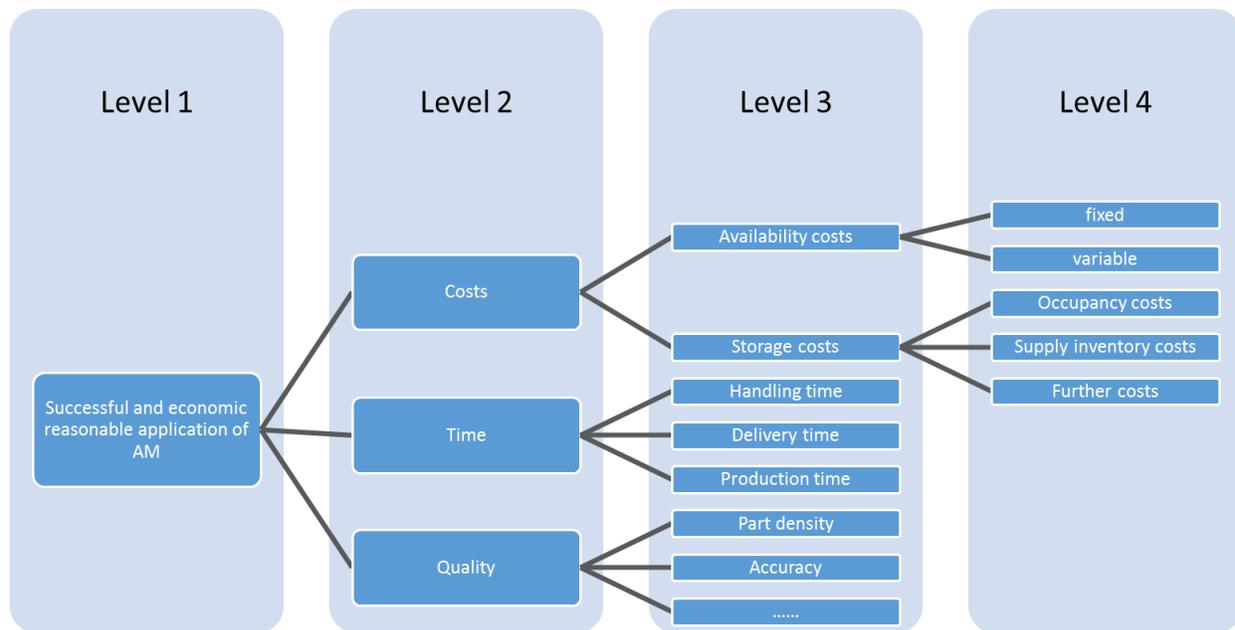


Figure 6: Approach for the decision model on the basis of the relevant criteria

The time aspect is reflected by the handling time for the processing of the order, the shipping time for delivering the part from the production site to the point of use and the actual production time for repairing or producing the part. All elements can be stated in hours.

The quality aspect is significantly more difficult due to more heterogeneous criteria. Overall it is problematic to describe quality as it is not directly measurable. For the decision support only quantifiable criteria has been chosen. The part density is an important factor for the durability of a part and stated in percent. A dimensional accuracy reduces the effort for post-processing or requires the anew production of a part in the worst case. The (highest) deviation is typically given in mm. The surface is not only important for optics but also for the reliability of the part as surface induced cracks can reduce the part's life time. As an indicator the mean roughness index is stated (unit:  $\mu\text{m}$ ). The last criterion is the process stability represented by the process capability index. It indicates the certainty of achieving a defined target and thus specifies a stable process. It is a dimensionless quantity. When transferring the described aspects to the existing use case, the model in Figure 7 can be composed.

	<i>Criterion</i>	<i>Weighting</i> [%]	<i>Min/Max</i>	<i>Preference</i> <i>-function</i>	<i>q-value,</i> <i><math>\sigma</math>-value</i>	<i>p-</i> <i>value</i>	<i>Unit</i>
Costs	Direct provision costs	8	Min	Type 3	n/a	500	\$
	Indirect provision costs	8	Min	Type 3	n/a	450	\$
	Occupancy costs	2	Min	Type 3	n/a	100	\$
	Storage costs	2	Min	Type 3	n/a	100	\$
	Other costs	2	Min	Type 3	n/a	100	\$
Time	Handling time	10	Min	Type 4	1	2	h
	Shipping-, delivery time	12	Min	Type 5	2	6	h
	Build time	10	Min	Type 5	1	2.5	h
Quality	Part density	17	Max	Type 3	n/a	3	%
	Accuracy (dimensional)	8	Max	Type 3	n/a	2	mm
	Surface condition	3	Min	Type 3	n/a	2	$\mu\text{m}$
	Process stability	17	Max	Type 5	0	5	-

Figure 7: Parameterization of the decision criteria

Based on

Figure 7 in combination with Figure 5 the preference function for the build time has an indifference area until 1 hour, after that there is a weak preference for the faster alternative. From 2.5 hours difference on there is a strict preference for the faster production process (see Figure 8). This value has been chosen on the basis of the reaction time in case of a work stoppage. A work stoppage occurs when an aircraft has a scheduled repair event but due to a missing spare part the work cannot be continued. The standard reaction time is then 24 hours until the spare part has to be available to meet further deadlines [Law10]. 10% of this time has been chosen to be the threshold until there has to be strict preference for the quicker production alternative.

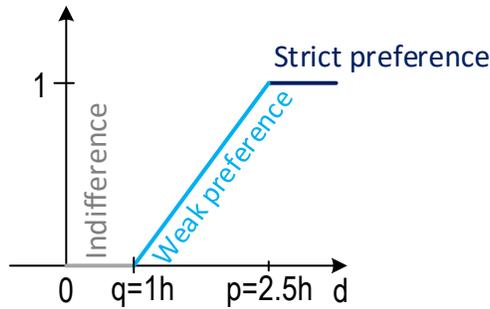


Figure 8: Example for a preference function for 'Build Time' criterion

Having all thresholds and preference functions assigned to the given criteria, the decision making process can start. Therefore, the input and output flows are determined for the different alternatives. The positive preference flow  $\Phi^+$  represents the strength of an alternative with values between 0 and 1. The higher the value, the better it is. The negative preference flow  $\Phi^-$  constitutes the weakness of an alternative where the values are between 0 and -1. The closer they are to -1 the weaker is the alternative. The sum of both flows sums up to the net flow  $\Phi$ . If this net flow is higher than a compared alternative this usually is the preferred one.

### Conceptual Design

In order to be able to use the decision support not only theoretically but also for real-world case studies the Decision Component is implemented as an Excel Tool in order to guarantee the ability to run on almost every standard equipped office computer. Excel is a spreadsheet analysis that is able to handle complex operations. Integrated formulas uses the user input to calculate a result. In addition to that, the software can visualize the generated data. To further extend Excel's opportunities, individual applications can be developed by utilizing the programming language Visual Basic for Application (VBA).

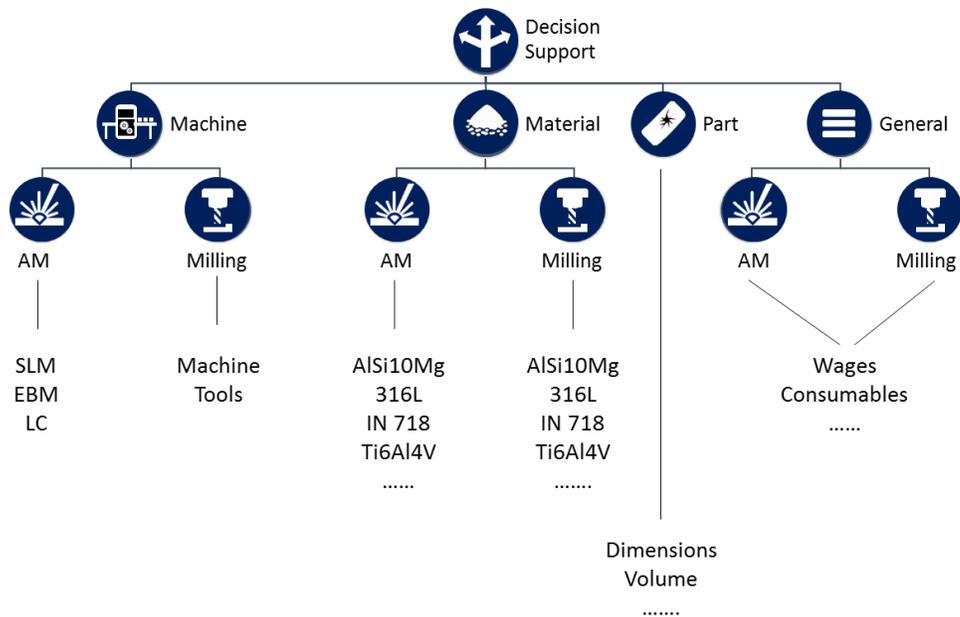


Figure 9: Overview of the configuration units for the Decision Component

The Decision Component is extended by VBA in order to enhance the functionality and the graphical interface which is shown in Figure 10. At the basis of the tool there is a calculation methodology for AM that has been developed at Paderborn University resp. the Direct Manufacturing Research Center (DMRC). In order to gather the required information for the calculation the tool is divided into different subsystems (see Figure 9).

They have to be filled in to provide the data basis for the calculation and decision making. This process can be supported by pre-defined master data that can be overruled but enables an easier operation of the tool. The system has to consolidate the given inputs and to ensure that all calculation relevant data is available.

When all configuration units have been filled in, the calculation can be started. The costs for AM, for milling and the procurement of a new part are calculated as well as the time aspect examined. The results are shown with different charts. The main cost drivers and their shares are shown as well as a quality, cost and time analysis. Based on the previously described methodology the preferred and cost- or time-efficient solution is determined. In order to meet the documentation needs of aerospace the tool creates several documents with all user input and calculation/result outputs and stores it in a defined directory. This increases the traceability for decisions that have been made and can be used to further improve algorithms etc.

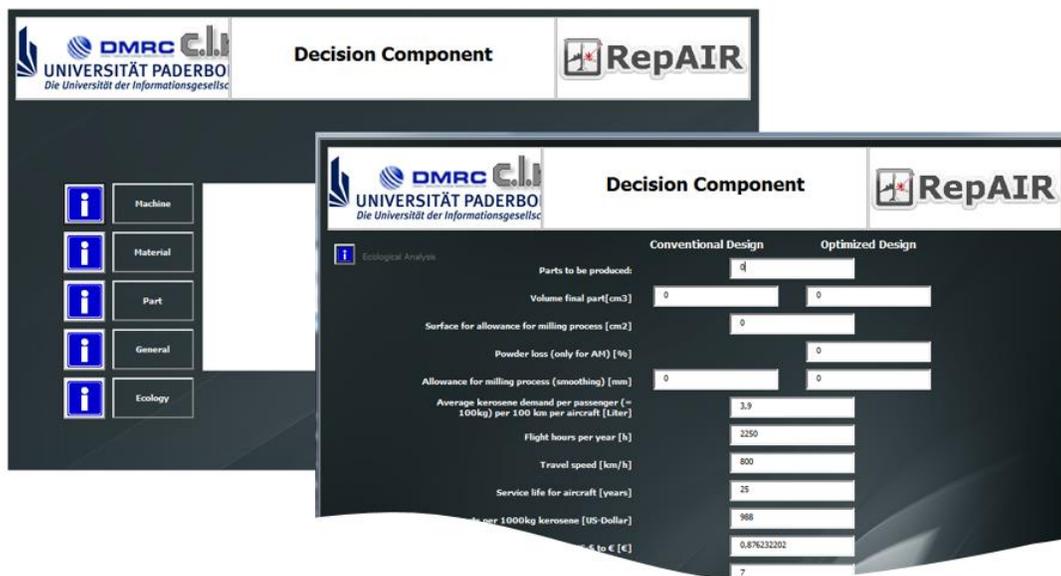


Figure 10: Start page of the tool and interface for one subcomponent

## Summary and Outlook

Due to the specific characteristics of aerospace, Additive Manufacturing is suited to be applied in the MRO aerospace industry. The required flexibility for low quantity and highly complex products cannot be realized by conventional technologies without reverting to extensive warehousing. The usefulness of applying AM for a certain use case has to be proofed. Therefore, a methodology is required that supports the decision process. Especially, because companies are

not experienced in assessing the production costs of AM and additional benefits have to be taken into account to fully exploit the benefits AM offers.

There are many options to use AM in the MRO business and creating potential economic and time benefits. To assess these benefits and to clearly state them a combination with software solutions is mandatory. This always has to be conducted in comparison to conventional technologies as AM is still limited in its utilizability. This will change when more experience with this technology is gained and more certified parts and processes will be available. The application of AM by OEMs and the prime manufacturers will foster this development as it will then become necessary at the MRO provider's side, too.

A framework to assess economic, time and quality factors has been developed and integrated in a software tool. Based on identified key cost drivers different configuration units have been set up. They provide a standardized process to gather data that is required for the calculation of the repair choices which is supported by predefined data but can always be adjusted manually. The tool then calculates the expected costs for AM and milling and the procurement of a new part from the OEM. The evaluation is illustrated by charts showing the share of each cost driver from the overall costs. Additionally, quality, costs and time graphs provide information of the key elements of MRO business showing the overall best solution for the defect part. This is still based partly on some assumptions, e.g. that qualified AM processes exists and the required quality can be achieved and proofed. The selection of an alternative is conducted by Multi Attribute Decision Making based outranking approach called Promethee which has been chosen due to the specific requirements and characteristics of the application. It is able to use different types of preference functions that can be applied for qualitative and quantitative influence factors. It is able to identify the best alternative even if this is not obvious or if there are strict preferences due to a time critical defect part.

The concept for the decision component allows the monetary assessment of repair processes especially of AM. The documentation of the complete input and output data fosters the transparency and traceability of decisions which is a crucial aspect in aerospace.

For future work a detailed comparison of sample parts/case studies is required in order to assess the validity of the tool. Therefore, the tool has to be improved in the evaluation of the quality and time aspect to allow a detailed analysis with real use cases and to fully exploit the tool's functionality. For future work the tool can be enhanced by strategic levels and additional functionality such as calculating the product life cycle costs or ecological factors. The aerospace specific tool could also be adapted to the needs and specifics of other industries in order to proof its general applicability.

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