REPAIR PROCESSES IN AVIATION: TOWARDS A SIMULATION-READY ASSESSMENT MODEL FOR THE EVALUATION OF PROCESS ALTERNATIVES

J. Aigner*, C. Trapp*, F. Raddatz*, G. Wende*
* German Aerospace Center (DLR), Institute of Maintenance, Repair and Overhaul,
Hein-Saß-Weg 22, 21129 Hamburg, Germany

Abstract

Efficient maintenance, repair and overhaul (MRO) processes in aviation ensure the operational readiness of aircraft. With increasing fleet sizes, the demand for coordinated, inter-aligned maintenance and repair processes increases. Many researchers focus on the development of new technologies and tools to optimize processes in aviation MRO. In academia, development of technologies is often assessed with respect to quality improvement, whereas in industry, repair processes are measured by economic considerations like duration and cost. Against the political and societal demands for sustainable aviation, the assessment of repair processes in aviation should also include ecological impacts like resource conversion. Therefore, for a detailed assessment of an MRO process, a multidimensional process model containing these aspects is developed in this publication. This model needs to meet the specific demands of aviation MRO: These processes are characterized by manual execution and individuality of process flows dependent on damage and part characteristics. The resulting lack of predictability incurs a significant overhead of communication, inspection and decision making. In addition to the high expectations regarding safety, quality and reliability, the capabilities and capacity of the repair facility are boundary conditions that need to be addressed. Therefore, a suited repair path needs to be chosen out of various repair alternatives defined by the availability of resources, technologies and tools. A modular, building block-based approach for the process model allows for various alternatives. As the degree of insight into part and damage increases along the repair process, the search space for the remaining process path is narrowed down. This systemically limited accessibility of a priori process planning leads to delays along the process and reduces its efficiency as the decision-making and planning for the next step is dependent on information generated in the previous step. Therefore, our approach allows for the simulation of various scenarios with information provision at different stages along the process chain as well as the evaluation with respect to the developed multidimensional assessment model.

Keywords
MRO Processes; Process Modeling; Process Simulation

1. INTRODUCTION

1.1. Motivation

The purpose of airplanes is flying. Therefore, the airworthiness needs to be guaranteed by recurring maintenance tasks, and in the case of unexpected damages, repair tasks. Thus, such processes are indispensable, but as they keep aircraft from flying, there is a high demand on efficient and effective maintenance, repair and overhaul (MRO) processes that, at best, reduce the duration during one MRO visit as well as increase the duration in between two MRO visits. Whereas the second demand is a research question in the field of predictive and prescriptive maintenance, the first demand, i.e. reducing the duration of one MRO visit can be answered by advanced process planning within the MRO shop. [1] Additionally to duration reduction, other factors like MRO cost or sustainability significantly impact the process planning within MRO shops.

1.2. Background

Despite the high demand on efficient repair processes in an MRO shop, current processes lack a reliable and certain process planning. This results from manual process execution and ad-hoc planning, meaning only after one step in the process chain is finished, the next process step is planned and executed. A previous study [1] shows for an example repair process that data-driven planning can reduce the MRO duration by half. Also, using advanced technologies for providing the data needed for data-driven decisions can positively impact other aspects in MRO shops, like the quality and digital maturity, resulting in a more effective process flow as well [2].
In both publications, the assessment is conducted a posteriori. This means, after MRO processes and possible alternatives have been conducted, they are analysed, compared and assessed.
As, however, MRO processes are not characterized (see section 2) by recurring events, but need to be planned specifically for each MRO shop visit, an a priori assess-

ment may provide the basis for planning the process in the most suitable way. By simulating different scenarios of possible MRO processes and assessing them with respect to given objective functions like duration, cost or quality, optimal solutions can be used as a template for planning the actual MRO process. This planning enables resource ordering as well as resource allocation. As MRO processes differ significantly from serial processes like production and manufacturing (see section 2), common simulation models for these industries, e.g. BPMN, cannot be easily transferred to the MRO field.

1.3. Research Question

With the demand for simulation models for process planning and the contradicting background of aviation MRO processes being individual and rather uncertain, the following research question is addressed in this publication:

How can MRO processes be simulated in order to predict the process flow as well as needed resources and their allocation.

For answering this question, it is separated into three subordinate questions as follows:
1) *What are the characteristics of MRO processes?*
2) *Which process and simulation models are suitable for these characteristics?*
3) *How can such models be implemented in the aviation MRO industry?*

In the following section, the characteristics of MRO processes are described. In section 3, different approaches in literature for modeling and simulating processes with similar characteristics and challenges - although from other industries - are summarized and compared. As the majority of scanned model approaches are not used in the aviation context, in sections 4 and 5 the MRO specific demands and constraints are described in more detail and our first approach to address them is explained. In the end, a short outlook for future developments and adaptations to further use-cases of the simulation model is given.

2. CHARACTERISTICS OF MRO PROCESSES

The following list summarizes characteristics of MRO processes that distinguishes them from processes in other industries that are planned, supported and controlled by models and simulations.

1) Low Quantity
   In contrast to recurring processes, e.g. mass manufacturing, the number of repairs in aviation MRO is quite low. According to the annual reports of major European MRO organizations [3, 4], the number of maintained aircraft ranges from 3000-4600. When comparing this number to major automobile companies [5–7] and their production rate ranging from 1.9 to 9.3 million produced cars, the number of maintained aircraft is rather low. In aviation maintenance, damaged components can either be repaired by replacing them or by repair the component itself. This means, for actual repair processes, in contrast to replacement processes, the number is even smaller.

2) Variability in parts and damages
   Despite this rather low number of aircraft to be maintained and repaired, the number of different parts in aviation is high. According to an OEMs repair capability list [8], the capability list includes more than 80 000 part numbers. This huge amount of components comes along with a significant number of different repair procedures, each for a specific component. Additionally, one component can be damaged in different ways, such that - depending on damage size and geometry - different actions are needed.

3) Unpredictability
   Damages may occur at any point in time. Thus, a long-term prediction and planning of repair processes is not possible. Aviation MRO shops do have experience values from previous years, so statistically, there is some knowledge about which repairs typically occur. However, it is not predictable at which point in time the damaged parts arrive in the repair shop.

4) Uncertainty
   If a damage has occured, the affected part is sent to repair. However, with the arrival at the workshop, there is no knowledge about the actual extent of damage, making the process uncertain. When dealing with MRO processes we encounter two distinct types of uncertainty (see FIG 1).

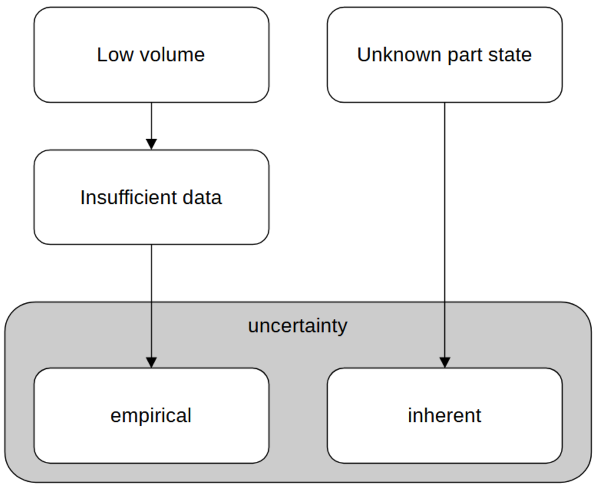

FIG 1. Types of uncertainty

The first, empirical uncertainty, results from the low volume nature of MRO work. Due to the limited amount and high variability as described above, sample sizes for statistical valid approaches are often not achieved. Secondly the initial state of the damaged part can be at best guessed as described in the above unpredictability description. This inherent uncertainty poses a major challenge towards the simulation of MRO processes as the identification of the actual state plays a large part of the repair process: According to [1], currently one third of the repair process duration passes until the state of the part is completely known.

5) Variability in tools and technologies
Similarly to other industries, also in aviation MRO new technologies and tools are introduced. Currently, repair processes are defined in a strict way, meaning even if digital technologies are used to gather information, they are squeezed into the surrounding, legacy procedures and documents. However, new technologies providing data in suitable formats can enable new process flows.

6) Short-term resource planning and allocation
Due to the above mentioned characteristics, MRO processes cannot be planned significantly before the actual process starts. On the contrary, due to the above mentioned uncertainty, many steps along the process chain are only planned in detail after the previous process step is finished. This results in short-term process planning and therefore resources, both in human resources as well as spare parts, need to be planned and allocated short-term. This characteristic is also found in many other industries, if e.g. resources fail, either by sick leaves or delay of spare parts deliveries. Nevertheless, in MRO processes this short-term planning is not an exception to long-term planned resource allocation but rather standard. Therefore, allocation of these experts and specific materials is a key topic in MRO process planning.

3. MODELING AND SIMULATION APPROACHES ADDRESSING THESE CHARACTERISTICS – LITERATURE OVERVIEW

Simulation is necessary in order to benefit from process models by providing ex-ante evaluation of processes and their alternatives by what-if analyses [9]. Despite the acknowledged advantage of simulation models for decision support on process modifications, the usage of business process simulation in practise and research is relatively low due to its complexity and missing technical expertise of users and the laborious construction of simulation models out of process models [9]. Such simulation models can be built on graphical process models like BPMN, EPC or Petri-net approaches, on mining event logs or on declarative process models [9].
For MRO processes characterized by low quantity, variability in parts and damages, unpredictability, uncertainty, variability in tools and technologies as well as short-term resource planning and allocation, simulation models need to handle these characteristics.
In the following, for each of the characteristics described above, some approaches in scientific literature to overcome these issues are outlined. This summary does not aim to provide a holistic literature review on the specific issues, but should rather underline that approaches tackling individual characteristics of MRO processes have been developed in the past and can be used and adapted for our use-case:

1) Low quantity
In contrast to serial productions in large corporations, processes with low throughput are often to be found in small and medium-sized enterprises (SMEs). Whereas mass production is characterized by high-volume, low-variety processes, the increasing mass customization requires low-volume, high variety processes [10]. According to [10], introducing processes with lower volume impacts the overall efficiency and decisions on job prioritization are rather on subjective criteria like personal experience or customer relations than on objective and strategic criteria. In order to overcome these issues and providing guidance for low volume processes, Sit et al. [10] develop a digital twin model providing intelligent simulation-based optimization model for job allocation and scheduling in dynamic environments. Their approach results in reduced waiting times for production order's starting points as well as improved productivity and on-time deliveries. Additionally to the above mentioned efficiency issues, small-scale enterprises are often facing a lack of technical expertise and infrastructure complicating the transition towards the implementation and usage of information and communication technologies [11, 12]. In [11], a production management system including real-time monitoring, order prioritization and task allocation is developed. Their approach enhances productivity and resource utilization. In [12], a digital factory for low-volume manufacturing processes is introduced increasing value creation by material flow simulation. In [13], fourteen different solutions for introducing agile processes in low-volume SMEs are summarized and described.

2) Variability in parts and damages
The above mentioned approaches [10, 11, 13] support low-volume, high-variability processes such that they can be used to address the variability in parts and damages. Additionally, there are publications addressing in particular the variability of processes, e.g. [14]. However, such contributions take rather a look on long-term process changes by change impact analysis and propagation.

3) Unpredictability
The unpredictability can be reduced if health monitoring and condition-based maintenance approaches (e.g. [15–17]) are introduced in aviation components. The transition from predicting the failure, i.e. predictive maintenance, towards prescriptive maintenance (e.g. [18, 19]) allows not only for predicting when a system will fail, but in particular which actions should be taken in order to restore the airworthiness. A recent publication on prescriptive maintenance [20] provides a holistic optimization framework considering different resources (labor, material, tools, equipment, infrastructure) as well as uncertainties and imperfections. With their approach, both revenue as well as dispatch reliability is improved significantly. The MILP optimization

approach provides decision support for maintenance planning of an airline fleet. However, it is not directly transferable to decision-making on aircraft level.

4) Uncertainty
For uncertain MRO processes, imperative process models like EPC or BPMN often provide insufficient freedom of design [21]. As the MRO process itself can only be planned along the process chain, a separation between build-time of the model and run-time of the simulation needs to be overcome [22, 23]. Different approaches providing this relaxation are adaptive processes [24], case handling [25], declarative processes [26] and late binding and modeling [27]. In particular, plan-driven approaches that are suitable for highly predictable and certain processes need to be replaced by agile or chaotic planning approaches [23]. Instead of describing processes a priori in imperative process models, with declarative models constraints can be defined that build the process model during run-time. For process-aware information systems (PAIS) Weber et al. [23] distinguished between three classes of constraints:
- constraints restricting the selection of activities
- constraints restricting the ordering of activities
- constraints restricting the use of resources.

In other publications, such flexible and uncertain processes are called knowledge intensive processes [21, 28]. As task durations, task ordering and the allocation of tasks and resources are difficult to define in advance, traditional workflow approaches are insufficient. Instead, process building blocks can be defined a priori and then be concatenated throughout run-time [29, 30]. These pre-defined process building blocks are concatenated depending on flexible boundary conditions as well as constraints that need to be fulfilled. Despite of promising advantages of such approaches for highly dynamic processes, they are still not widely adopted in practice. Due to the low practical usage, there is no evidence on how the users handle the high degree of flexibility [23, 31].
An apparent paradox of such flexible process models is outlined in [32]: Whereas process models aim to predict process flows and provide guidance for the execution, users want the process models to be as flexible as possible. Different types of flexibility of process models as well as suitable supports for them are described.

5) Variability in tools and technologies
As described in the previous section, the variability in tools and technologies is not limited to the aviation MRO sector. However, as different tools perform differently and can provide different outputs, process flows can be dependent on the used tools. Furthermore, they will behave different in various aspects, e.g. conventional tools might be cheaper, whereas digital tools might be faster and of higher quality. These aspects are covered in publications on technology assessment rather than on process simulation. However, the different assessment criteria of different tools as well as their output needs to be used as constraints in process simulation models.

6) Short-term resource planning and allocation
Resource planning and allocation often comes along with process planning. Therefore, with the short-term process planning as described with uncertain process flows, resource allocation needs to be handled in these approaches as well. However, in [31], the allocation of human resources is described as "probably the biggest problem of current business simulation approaches". As people are involved in multiple processes, they do not work at constant speed, but work part-time and in batches, priorities are difficult to model and processes may change depending on contexts, simulated process models predict flow times of minutes or hours, whereas in reality durations are weeks or even months [31]. Thus, these difficulties of resource allocation for process planning complicate the short-term planning approaches described above.

4. BUILDING BLOCKS IN MRO PROCESSES: TOOLS

In order to answer the third research question of our publication, this section describes the tools that aim to meet the requirements as outlined in the previous sections. Especially, the ideas of the provided literature are combined such that the simulation of an MRO process can be realized. Basically, two developed programs are introduced in this section.

4.1. Structured Aircraft Maintenance Documentation (SAM-D)

With SAM-D we have a software package that has been developed to extract process (step) descriptions with their dependencies and resources from existing maintenance manuals. An example of this is shown in FIG 2. The aim is to analyse possible execution orders of steps and the identification of overlapping parts of defined maintenance processes. To this end process steps are arranged in a directed acyclic graph that represents all sequences of their execution as described in the underlying document. This precedence graph may contain any number of connected components. The connected components typically cluster around one distinct part of the aircraft, we add the one representing the maintenance work on a horizontal stabilizer in FIG 2. Note that the tasks have been somewhat generalized so 'REMOVE/OPEN FOR ACCESS' may refer to the removal of several different panels.
The precedence graph represents all logically possible sequences, of which several may not be sensible. For example the topmost node allows an infinite sequence of removing/opening panels. In the context of the current research project, SAM-D is extended to allow the functional evaluation of the involved environment, so in our experiment we interdict infinite repetitive behaviour by tracking the shop and part states. Due to updating the

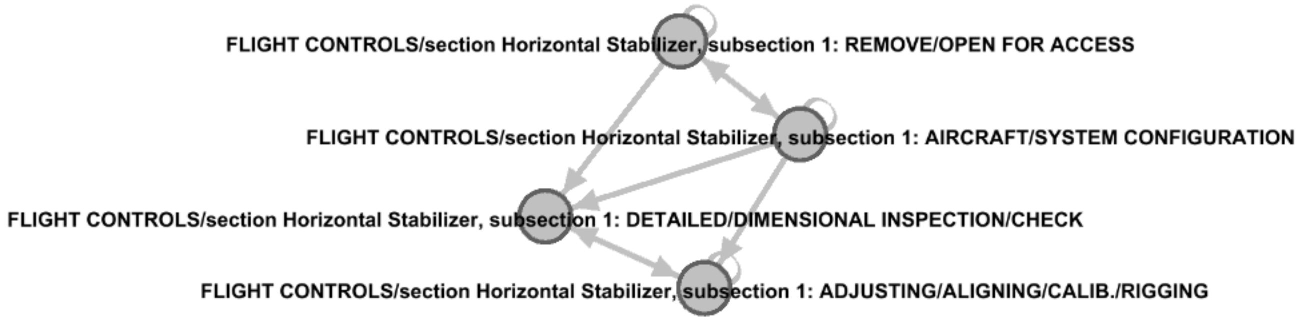

FIG 2. Precedence graph of tasks surrounding the adjustment of a horizontal stabilizer.

environment after each actualized step, we would simply run out of unopened panels after a short while.

4.2. Impact Factor Propagation and Management: IP-MAN

IP-MAN has evolved from a system health index framework that has been used to support predictive maintenance [33]. It is able to describe more general system states and the ways a system's components affect each other. For our application we define the repair shop and the damaged part as components and the actualized process as a property of the shop. At each step of the process creation we identify possible steps within the constraints of the shop's resources and capabilities. Whenever more than one possible extension of the so far assembled process is being encountered, the system will be duplicated and all possible paths explored. This includes the stochastic implementation of process steps that have more than one possible outcome, as it is common for inspection tasks.

5. IMPLEMENTATION

With the two packages described in the previous section, a self-assembling, simulation-ready process model will be provided. As the implementation is not finished by the date of this publication, the functionalities are described. For implementation details as well as validation and possible future studies (see section 6) conducted with this model, we refer to future work.

5.1. State tracking: IP-MAN

Due to the characteristics of MRO processes, constraint-based process modeling and simulation is desired. Constraints can either be fulfilled or not, depending on the *state* of the surrounding system. In the case of MRO processes, the surrounding system is the MRO shop itself as well as the parts to be repaired.

The state of the MRO shops includes all maintenance resources [20] comprising human resources, material, tools, equipment. Regarding resources, the distinction between consumables and durables is necessary.
Consumables are consumed when used. Spare parts and materials are used during maintenance and repair, meaning their stock is permanently reduced in the process.
In contrast, durables are "busy" during the process execution, temporarily reducing the stock, and replenished afterwards. *After* the process step is finished, the durables are returned to their stock, see FIG 3.

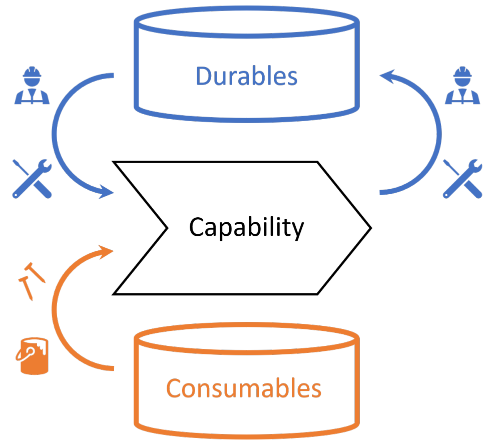

FIG 3. Durables vs. Consumables: Durables return to stock after their usage whereas consumables are used, resulting in a reduced stock.

Additionally to the state of the MRO shop, also the state of the part to be processed needs to be tracked.
The part state includes part characteristics, damage characteristics as well as procedural characteristics.
Part characteristics include general information like size, geometry of the part, as well as material properties or part history.
Damage characteristics include location, size and geometry of the damage. In particular, the damage characteristics are not known at the beginning of a process.
Procedural characteristics describe the *current* state of the part along the MRO process: For example, procedural states could include intermediate states like "inspected", "panel open", "paint stripped" or "repair completed". The degree of so far acquired insight into the actual state of the part is considered an operational characteristic as well.

5.2. Process Database: SAM-D

Different available capabilities (see FIG 5) of an MRO shop are stored in a process data base. These capabilities are individual process steps. Each of these capabilities has the same structure as shown in FIG 4:

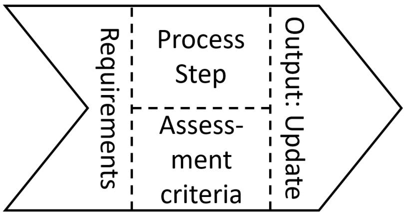

FIG 4. Capability structure including process step, requirements, assessment criteria and output:update.

1) Process Step
2) Requirements
3) Assessment Criteria
4) Output: Update.

5.2.1. Process Step

Each entry in the process data base has a name, description and index of the process step itself. This serves mainly debugging and visualization purposes but also fulfills some of the demands of the underlying software solution.

5.2.2. Requirements

For each capability, requirements are given. These requirements cover both the current state of the MRO as well as the state of the part.
E.g. for the process step "repair", the requirements on the state of the part could be

- part suitable for mounting jig
- damage size exceeding allowable damage limit
- part inspected.

This example shows requirements on part characteristics, damage characteristics and procedural characteristics.

In addition to the requirements on the part, also requirements on the MRO shop need to be fulfilled. Sticking with our example process step "repair", those could be

- one mechanic is available
- repair tool "scarfing" is available
- material "composite" is available
- material "adhesive" is available.

The first two requirements address durables: Both human resources as well as tools will be set to "busy" during the process step and afterwards go back to the pool. This means, for following process steps they can be used again.
In contrast, the last two requirements address consumables: Both the composite material as well as the adhesive will remain with the part after the process step. This results in the stock reduced by the amount of composite and adhesive used. In particular, this means, for following process steps, less resources are available.

5.2.3. Assessment criteria

The process model and simulation aims to provide decision-support on the choice of possible process alternatives in order to get the "best" MRO process. Thus, for decision-making, different process alternatives need to be compared with respect to different assessment dimensions [2]. Thus, assessment criteria need to be included in each process step. These criteria can consider different assessment dimensions, e.g. economic aspects like cost and duration, quality, ecological impact or social aspects. The assessment criteria are restricted to quantitative measures such that clear numerical values can be provided in the end.
A concatenation of the assessment criteria along the overall process chain provides a *process value*. For example, the process value "cost" will be the added sum of the cost of the individual process steps.
One special feature is the process duration: On the one hand, this is an assessment criterion like cost and quality, on the other hand the duration of the process steps defines how long durables are in the state "busy" and thus, cannot be used for other process steps.

5.2.4. Output: Update

Each process step produces output both on the state of the MRO shop as well as on the state of the part: For our example of the process step "repair", the procedural characteristic is updated to "part repaired". There might be states that are not affected by the process step, e.g. the part size will not change. Therefore, these states will remain the same.
The MRO shop is updated by setting the durables to the state "free", and reducing the stock of the consumables.

The level of detail of the process steps in the process database is not restricted, meaning one process step could be one individual task of an repair order, and another process step could be the overall inspection process. The granularity can be adjusted to different use-cases.

5.3. Self-Assembling Algorithm

The method for automated assembly of process flows is schematically shown in FIG 5.

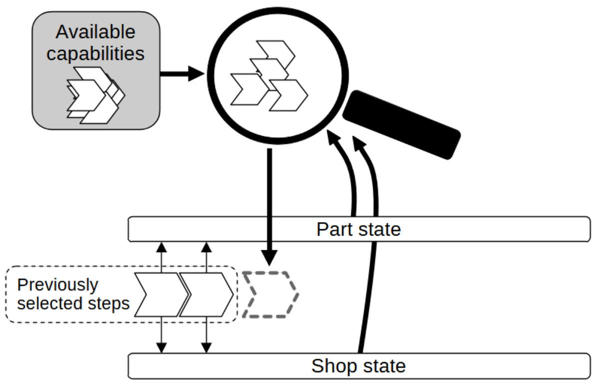

FIG 5. Automatic assembly of processes

After each actualized process step, the whole collection of shop capabilities in combination with the resulting state of the environment is used to create a precedence graph. We then use the graph to find possible subsequent steps to extend the existing process chains. The key ingredients to this are the final step of each so far assembled process chain and the defined desired final step of the overall process, e.g. for MRO processes the task "release part to customer". With this we can filter the precedence graph for connected components that contain both key steps and take the direct descendants of the entry point into further consideration. In the likely case that more than one solution exists, the assembled process and its environment is duplicated such that all options can be explored in the following iterations. Each duplicate contains another actualized path, see FIG 6. This is repeated until we no longer can create a precedence graph that fulfills the requirements of subsequent step identification. Environments hosting process chains that do not yield the desired result can now be discarded and the valid process chains can be assessed.

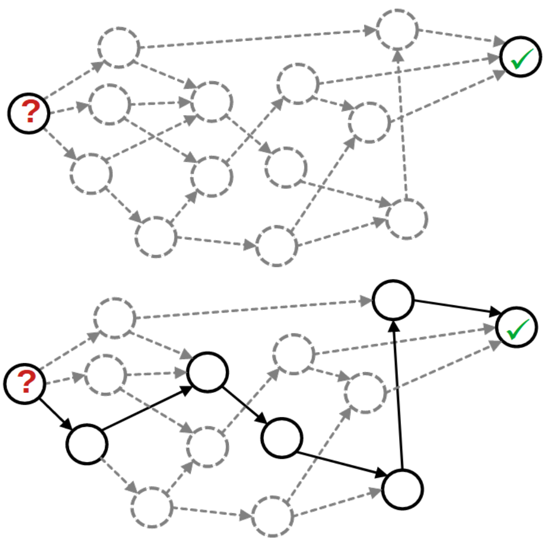

FIG 6. A precedence graph containing all possible paths vs. one actualized path

5.4. Future Work

The described self-assembling methodology is still in the beginning of its technical implementation. Once implemented, the next step is to include parallel processes (see e.g. [1]) and loops within the process: For example, for MRO processes, it is typical to evaluate the damage in a non-destructive testing (NDT), then remove some of the damaged material, repeat the NDT, remove further material, and so on.

Once the self-assembling algorithm itself is technically implemented, it can be used for different studies:
Different technologies and their impact on the overall process chain can be assessed, resource utilization can be modeled and improved or uncertainty propagation could be investigated.

6. CONCLUSION AND OUTLOOK

In this publication, a work-in-progress approach for modeling and simulation of MRO processes is described. The different functions and relations are provided. However, at the current status, the model is not fully implemented. Thus, in order to use it for future studies like resource management, hangar planning or process optimization within MRO organizations, it first needs to be technically implemented, valid capabilities need to be provided in the process data base including their requirements, assessment criteria and update functions.
In addition to the practical implications and studies, further research should focus on quantifying the characteristics of MRO proceses as described in section 2. In particular, the literature summary in section 3 can be expanded to a structured literature review specifically designed to compare the different approaches and relate our approach to existing approaches.

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Contact address:

mailto: johanna.aigner@dlr.de

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