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ASSESSMENT OF THE ASSEMBLABILITY OF AERO ENGINES ON THE BASIS OF A LPT MODULE

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Abstract

The aviation industry and air traffic have been growing constantly for the last decades and an end of this trend is not predicted for the next decades. As a result of this the pressure on aero engine manufacturers is increasing to evaluate life-cycle related costs of future products as early as possible. One aspect of this is the assemblability of the product which is initially assembled at the OEM's production facility but later on it is also subject to Maintenance, Repair and Overhaul activities. Since assemblability has a significant influence on life-cycle-related cost a systematic method for the evaluation of assemblability during preliminary design is proposed in this paper. The developed method considers the boundary conditions that are necessary to evaluate the assemblability of an aero engine during preliminary design, which only exists at a low level of detail in this phase. The method considers requirements of the preliminary design concept, the assembly process, and the assembly system in order to derive characteristic inter-dependencies and assembly time allocations of the chosen concept. Subsequently, the developed method will be applied to a Low Pressure Turbine module to discuss the effect of the Level of Detail on the assembly time estimation.

NOMENCLATURE

CAD	Computer Aided Design
LoD	Level of Detail
LPT	Low Pressure Turbine
MTM	Methods Time Measurement
OEM	Original Equipment Manufacturer
PD	Preliminary Design

1 INTRODUCTION

As a result of the constant growth of global air traffic the demand for new airplanes and hence new aero engines is increasing [2]. Since the production capacity for aero engines is not growing as fast as the projected demand of new aircrafts the backlog of orders might rise [2, 6, 14, 16]. In order to accept this challenge for future and today's products, the throughput time from order to delivery within the companies has to be reduced. The overall producibility of aero engines has to be improved significantly to achieve this. Therefore, a transition process from a manufacture-like small series production to a series production, which can handle the growing demand is needed. Enablers in terms of throughput time of this transition from a technologically feasible product towards an economically producible product are specifically the assemblability of the product and its sub assemblies.

Previous research in the field of preliminary design of aero engines mainly focused on aerodynamics, performance, engine weight, and dimensions of the aero engine concept [4]. In order to increase competitiveness, it is essential to additionally evaluate a future product and its assemblability as early as possible. Hence, an approach for the assessment of the assemblability of aero engines during preliminary design will be presented in this work.

2 PRODUCT DEVELOPMENT OF MODERN AERO ENGINES

The product development process of new aero engines typically is organized in different development stages. As of the large investment cost and significant development time , this formalized process is feasible. Nevertheless, estimation of the costs of a new engine project is difficult because of increasing material and labor costs as well as increasing costs for qualification and certification [9, 10, 12, 15].

A typical Product Development Process for aero engines can be broken down into five major phases, the first phase being Preliminary Design. [10]. The importance of preliminary design in the overall product design process because of its impact on architecture, weight and dimensions, as well as life-cycle related costs is undoubted. To aid in the process of generating as much knowledge of the product as early as possible, numerous computer based tools such as GasTurb, NPSS, MOPEDS, PMDO, Genesis etc. were developed by research institutions and aero engine OEMs [4, 8, 12, 13, 17].

In order to increase the knowledge of the product during preliminary design even further, assembly informa-

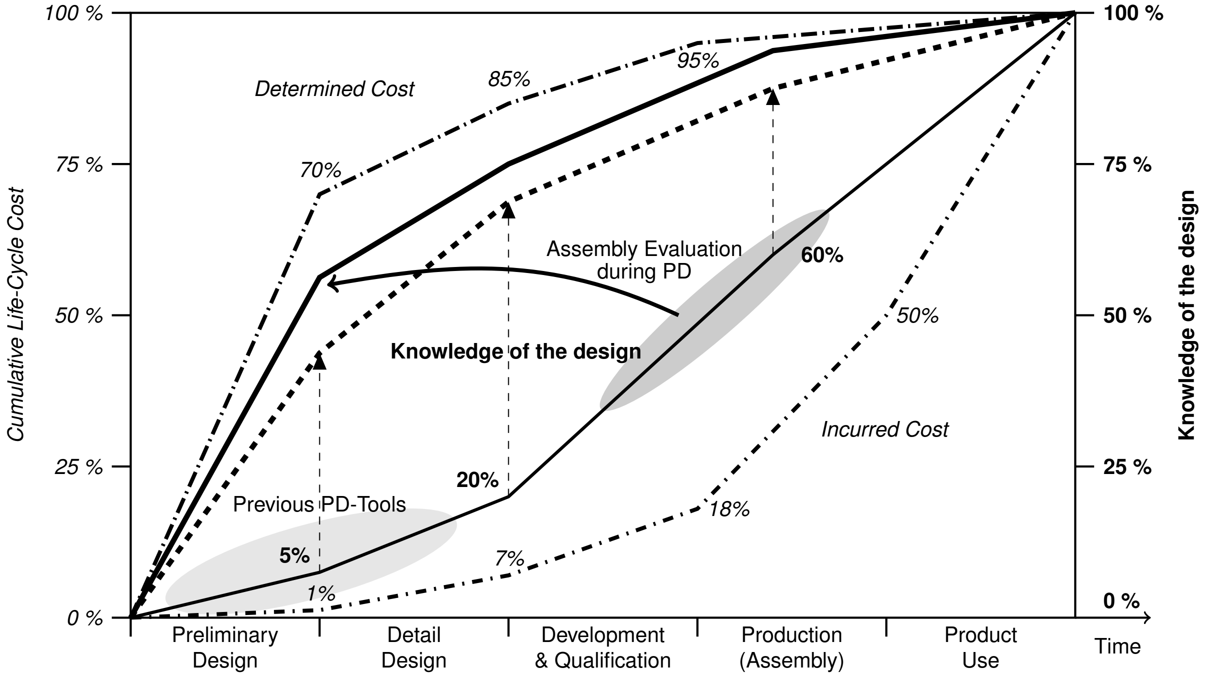

Fig. 1: The cost of design vs. knowledge and the advantages of PD-Tools

tion need to be considered to evaluate the assemblability. However, the knowledge of the design is linked with Life-Cycle Cost because more knowledge of the design allows more profound decisions, which influence the downstream design activities.

Fig. 1 displays the typical progressions of costs and knowledge for an aero engine project along its development cycle. During preliminary design, the amount of incurred costs is very low with 1% as well as the knowledge of the design with 5%, whereas 70% of the costs are determined through design decisions in preliminary design. Aided by computerized preliminary design tools, the amount of knowledge about the product can be increased early on, which is displayed by the thick dashed line in Fig. 1. [4,7,10]. Assembly evaluation is typically conducted in later phases, such as development & qualification and production [3,5]. However, the incorporation of assembly information as well as information about tools, fixtures, and workers into preliminary design activities increases the knowledge of the product even further, as indicated by the bold line. Eventually, this leads to time and monetary advantages because the knowledge about the product as well as knowledge about the corresponding assembly system is generated simultaneously, and therefore the latter can be analyzed and specified at an early point of time in the product development process [10,12,18].

3 ASSEMBLABILITY

In order to conduct assembly evaluations in early design stages, a detailed analysis of the overall product structure is necessary. In this context, the concepts needs to be analyzed to understand the interactions of design features, product architecture, and assembly processes on the assemblability.

Assembly refers to all processes of combining different manufactured and geometrically defined parts to form a final product. A product in this context may only consist of parts or of different sub assemblies and parts. Typically, assembly is the last value added step of production [11]. The method of assembly can be defined as the way how parts, sub assemblies and fasteners are assembled to form a final product with regard to different technological constraints and therefore characterizes the assemblability of the product [3,11,18,20]. In general, a limited number of sub tasks of assembly can be defined, as displayed in Fig. 2. These sub tasks are linked to the superordinate assembly system as well as to product elements, such as parts and fasteners. However, the assembly system is an integral part of production and the overall product development process and therefore influences the assembly process as a whole. As seen in Fig. 2, certain product elements influence the assembly process and vice versa. To assess the assemblability of a product different considerations of interdependencies between assembly process and product elements need to be conducted, especially in a development phase with

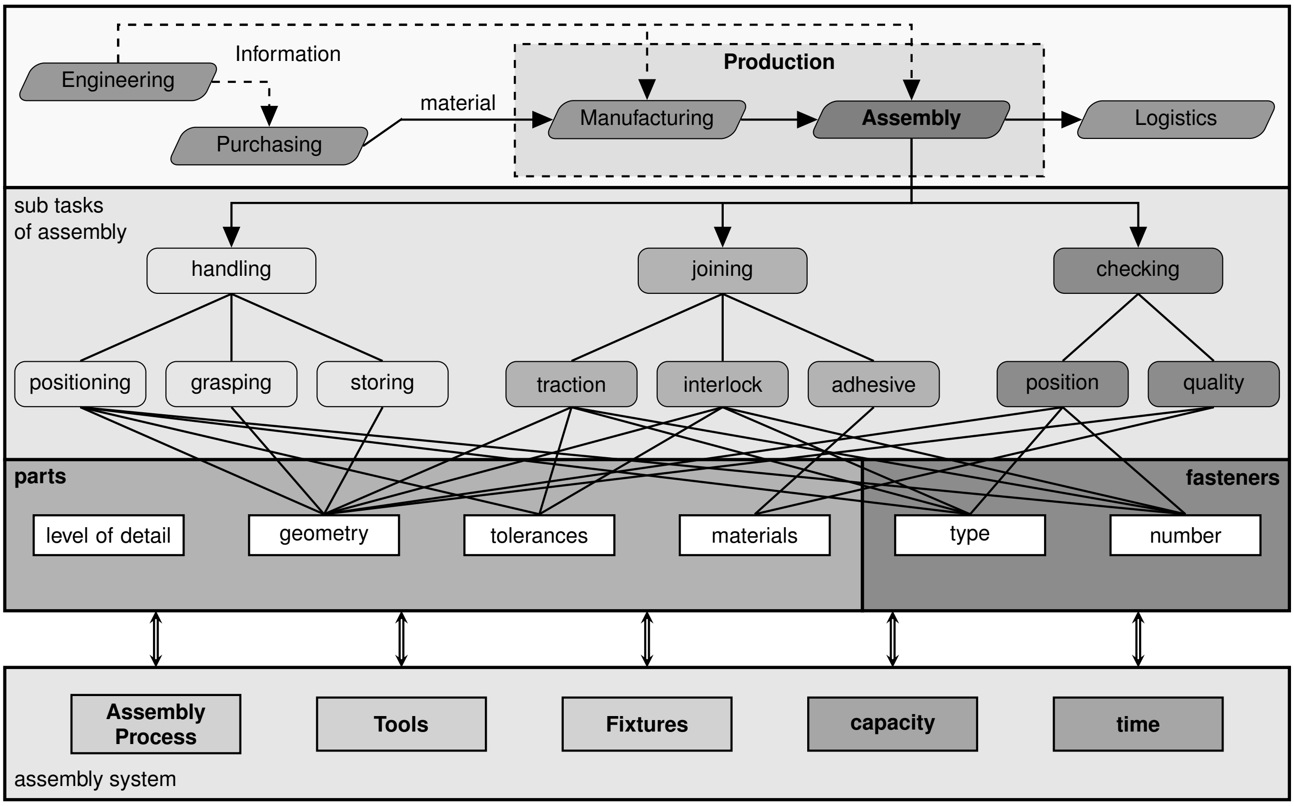

Fig. 2: Inter-dependencies of product elements and the assembly process

limited knowledge about the product and the eventual assembly system.

Digital assemblability evaluation

A method for the assessment of assemblability in early product development phases is the digital product validation method proposed by WACK et al. [18], which utilizes digital models for the assembly evaluation at different levels of detail, as seen in Fig. 3.

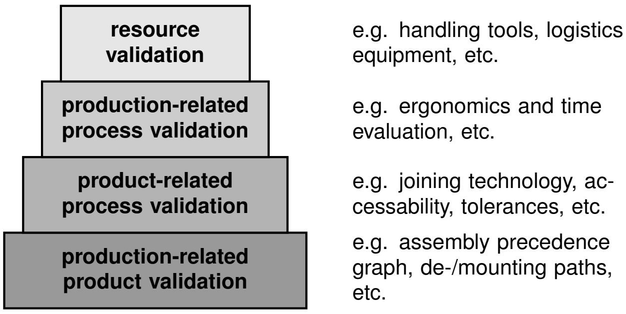

Fig. 3: Assemblability evaluation through digital product validation [18]

The different stages of the design process are executed in CAD systems. During this stages a lot of digital data is generated, which can be used for digital assemblability evaluation in an early stage to validate the product and future assembly systems. Through such an approach, cost and time advantages can be utilized, such as a reduction of physical assembly ramp-up tests, earlier knowledge of assembly equipment, and early training of assembly personnel [18, 19]. WACK et al. propose a 4-stage model for the digital product validation prior to a production ramp-up, as displayed in Fig. 3. Based on a production-related product validation, the designed product is evaluated in terms of buildabilty. For instance, collision analyses of parts along the mounting and demounting paths are executed as well as different assembly sequences, which can be described in assembly precedence graphs to evaluate the product during this stage. During the subsequent stage of product-related process validation the value added processes for the assembly of the product are analyzed. This includes for example different joining technologies, tolerances of the parts, as well as the accessability of joining elements. In the following stage, a production-related process validation will be conducted, which also includes non-value added aspects of assembly such as ergonomics and workstation layout. In addition to that, time estimations and evaluation can be conducted as well. To conclude the digital product validation, a resource validation analysis is conducted at last, which mainly includes logistics equipment (e.g. carts, boxes, etc.) and aspects of the assembly system as well as handling tools [18].

4 METHOD FOR THE ASSESSMENT OF ASSEMBLABILITY DURING PRELIMINARY DESIGN

Given limited resolution of predicted details during the preliminary design of aero engines, only a certain amount of accuracy can be expected from an evaluation of assemblability at this stage.
Based on the method of WACK et al. [18] only the stage *production-related product validation* can be evaluated in a satisfactory manner during preliminary design. Depending on the level of detail of the preliminary design concept the stages *product-related process validation* and *production-related process validation* can be carried out partially. In order to achieve feasible results for further design considerations the systematic method for the assessment of assemblability during preliminary design is derived as displayed in Fig. 4.

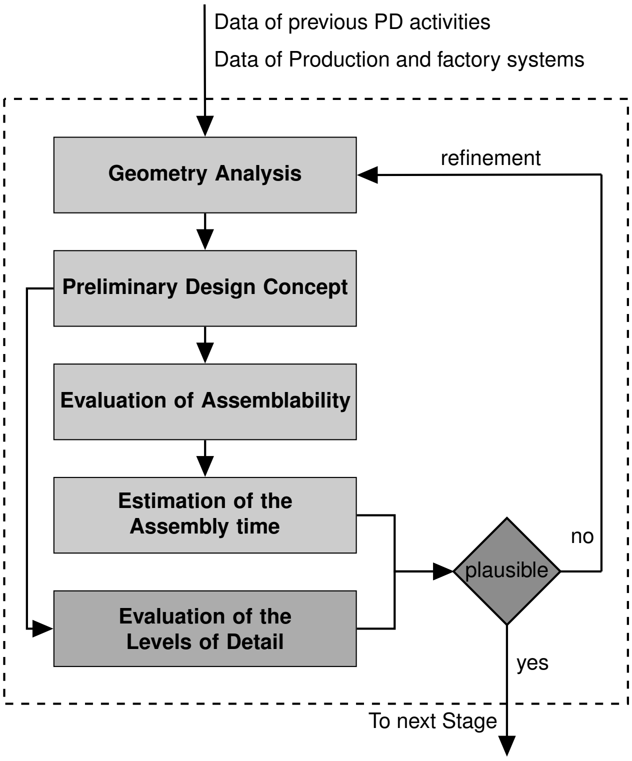

Fig. 4: Systematic procedure of the deduced method

Geometry Analysis

The starting point is a geometry analysis similar to the consideration displayed in Fig. 2. The proposed data of the preliminary design tools and activities as well data of the production and involved factory systems (e.g. fixtures and tools, assembly process experience, capacity) are analyzed. The focus lays on the detection of inter-dependencies of product elements and technological aspects of the assembly system.

Preliminary Design Concept

A simplified, fully parametric 3D CAD model is set up to assess the preliminary design concept in terms of assemblability. The model is based on a parameter-table, which includes all geometric information of the parts and therefore allows direct links between the dimensions of adjacent parts. In addition, the number of parts, specific design features, as well as the spatial position of parts and subassemblies can be specified in the parameter-table.

Evaluation of Assemblability

Different mounting and demounting paths are evaluated manually in the CAD system. In addition, an assembly precedence graph is generated manually. This graph displays the sequence of tasks in which the different components are combined to form the LPT module [5].

Estimation of the Assembly time

Based on the assembly precedence graph, the different assembly tasks can be evaluated with different methods to estimate the required time for the execution of the specific workloads. The manual assembly processes are evaluated with the MTM method, which utilizes standardized work step elements for the estimation of the required assembly time [1]. In this context, MTM is used as a remote analysis tool based on the geometry of the CAD model. The evaluation steps are performed without previous experience of manual assembly steps in the factory environment.

Evaluation of the Level of Detail

The generated simplified 3D CAD model serves as the basis for the calculation of the Level of Detail of the concept. This figure of merit is calculated through a separation of the LPT module in different subgroups and features. The features are rated with 0 (not considered), 1 (sketched/estimated), and 2 (designed with common rules). The average score of all the considered subgroups eventually resembles the Level of Detail. Depending on the focus of the concept, different subgroups may be defined and evaluated.

Plausibility check

In the final stage of the method, weight and part count estimations are conducted as well as an assembly time estimation. Through these evaluations the exploration of the remaining design space and further design activities can be conducted more target oriented. If the results are not plausible, a refinement loop may be initialized.

5 APPLICATION OF THE METHOD AND DISCUSSION OF THE RESULTS

In order to test the suitability of the introduced method it is applied to a 5-stage LPT module of a civil aero engine at two different Levels of Detail (LoD). A 3D CAD model of the LPT served as a reference.
As a means to classify the different parts of a LPT module, the following distribution is proposed. Parts or components, that are dependent on the chosen architecture are classified as A-parts (e.g. case, discs, blades, vanes). Parts that are necessary to fixate A-parts are classified as B-parts (e.g. fasteners, seal plates). Additional parts that are subject to later design activities are classified as C-parts (e.g. cooling manifolds, blade dampers, bearing structures).

5.1 Parametric 3D CAD model

In order to achieve a suitable parameter set for the set up of the parametric CAD model, different simplifications were made. As an example, circumferential grooves are displayed in Fig. 5, which serve as the interface of the case for vane segments as well as tip seals. Both, vane and seals, engage the groove utilizing a key with the respective geometric values.

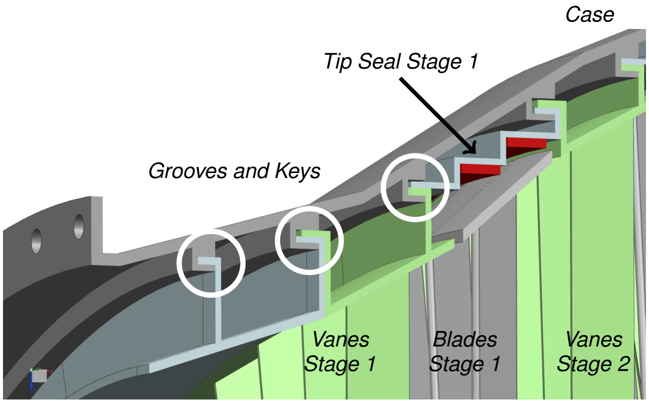

Fig. 5: Simplified interface of turbine case

The first evaluation considers only A-parts of the 5-stage LPT module. According to the introduced method for the calculation of the Level of Detail in sec. 4 this results in a LoD of 55% (LoD A). Following the geometry analysis, the simplified, fully parametric 3D CAD model is set up as displayed in Fig. 6. The model is shown on a simplified assembly fixture and comprises one case, five discs, a total of 277 blades, vane segments for each turbine stage, as well as tip seal segments. The numbers of blades and vane segments are derived from the reference model whereas the numbers of tip seal segments are estimated. External accessories, as well as the LPT shaft are not considered at this point.

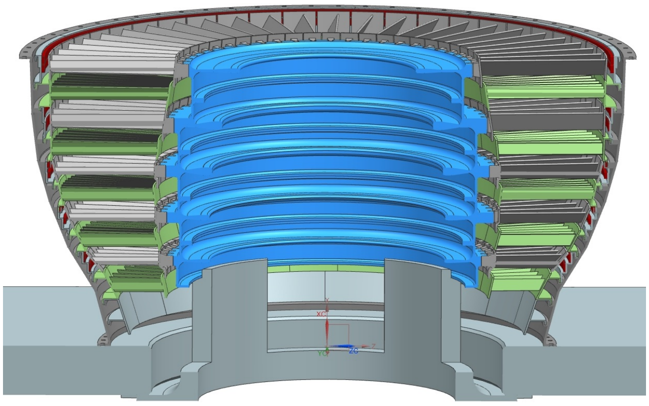

Fig. 6: 3D CAD model of evaluation with LoD A - only A-parts

The second evaluation additionally considers fasteners (F) and seal plates (S) as representatives for B-parts, as displayed in Fig. 7. The quantities of seal plates and fasteners between the different turbine discs are estimated. The Level of Detail is calculated to 61% (LoD B).

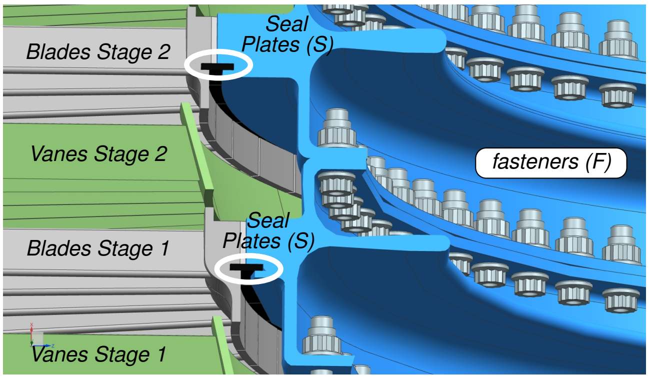

Fig. 7: 3D CAD model of evaluation with LoD B - A-parts with fasteners (F) and seal plates (S)

5.2 Discussion of systematic relations

In general, certain dependencies can be derived, which influence the evaluation of the assemblability of a preliminary design concept more than others (e.g. number of blades on a rotor). In addition, different design features show a direct dependency on the chosen architecture of the concept. In order to minimize the necessary efforts for an evaluation of the assemblability, different interfaces within the LPT module such as flanges or firtrees of blades and discs can be estimated on the basis of standard times.
Based on the generated 3D CAD models, different mounting and dismounting evaluations are conducted

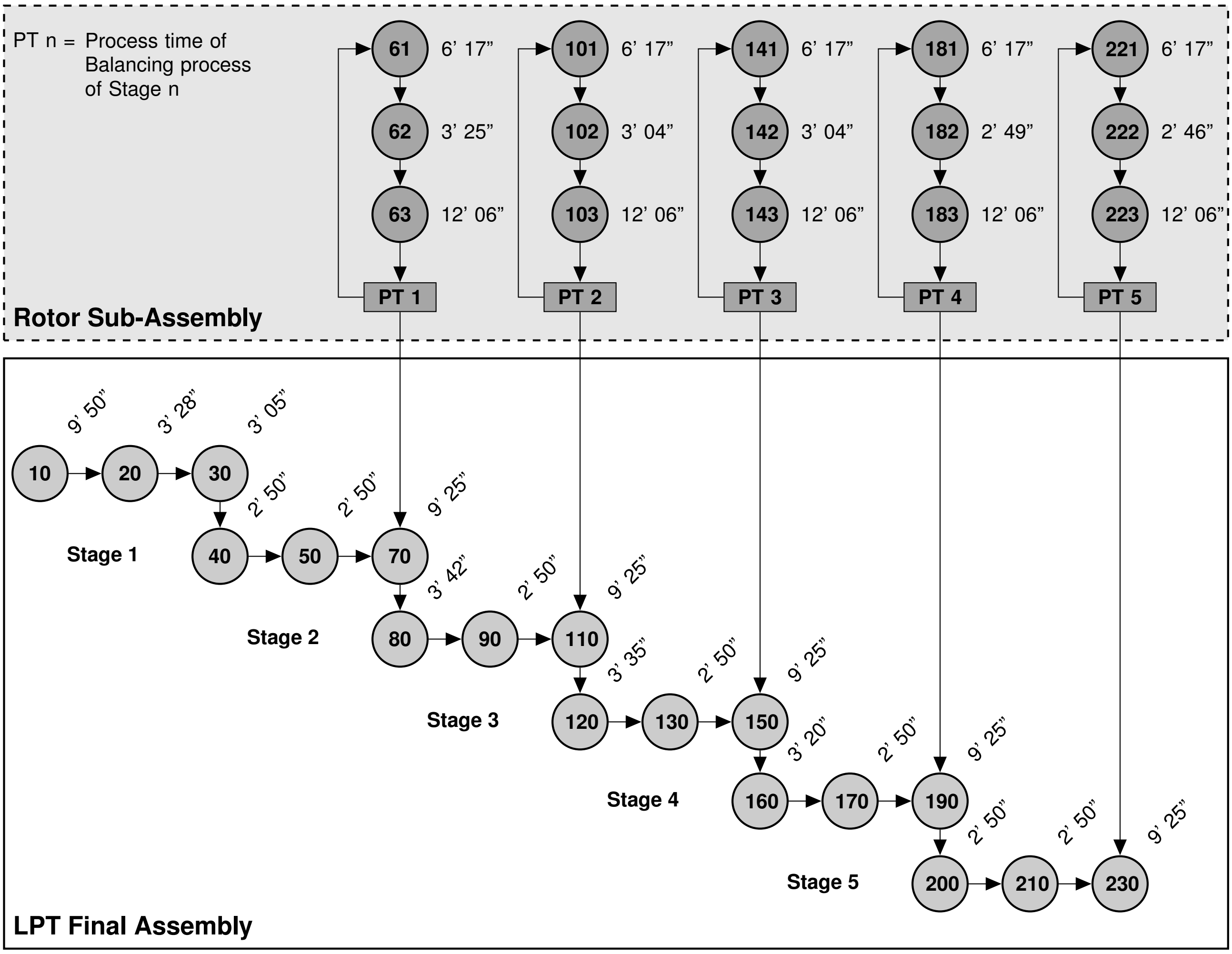

Fig. 8: Assembly Precedence graph with estimated manual assembly times for LoD B

manually, which provide findings for the Evaluation of Assemblability and the set up of the assembly precedence graph. The assembly precedence graph of LoD B of 61% in Fig. 8 displays the different tasks in a consecutive order that are necessary to assemble the considered product concept. In addition to that, different tasks are displayed in a sub-assembly section, which can be conducted parallel or detached from the final assembly process. These parallel tasks comprise the task for pre-assembling the rotors of the different stages. In the final assembly section, the characteristic consecutive sequence of the different turbine stages is displayed. Subsequently, the different manual assembly tasks, which were defined in the assembly precedence graph are analyzed with the MTM method to estimate the assembly time. The results of these estimations are also displayed in Fig. 8.

In general, any LPT of an axial turbo machinery follows an assembly structure similar to Fig. 8. Although, based on the chosen architecture of the concept (e.g. number of stages, interfaces, etc.), this structure varies in the quantity of the stages whereas the overall structure of the assembly precedence graph remains the same.

5.3 Results

The results of two evaluations with different Levels of Detail are displayed in Fig. 9. The first LoD A with 55% comprises only the A-parts and manual assembly work steps while the LoD B of 61% also considers B-parts such as fasteners and seal plates as well as the necessary assembly steps complemented with estimated process times for the balancing of the rotors.

The results of the design related weight estimations and part count for LoD A show a distribution which is similar to a Pareto distribution. This means that 30% of the parts account for 68% of the weight of the LPT module. The estimated assembly time for A-parts is low with 6% compared to similar product in production. The results for LoD B with 61% display only a minor increase in the estimated weight of the LPT module to 70%, whereas the part count increases significantly

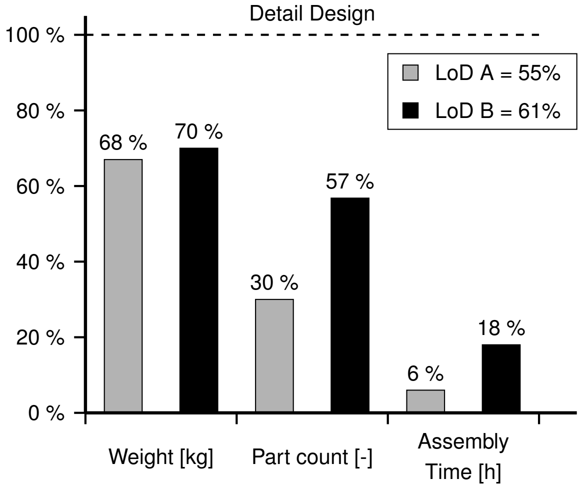

Fig. 9: Results of two assembly evaluation iterations

to 57% due to the fact that a large number of fasteners is necessary to connect the different stages. The assembly time increases significantly to 18% with the consideration of B-parts. One of the reasons is the increased part count as well as the more complex operations of installing fasteners in limited space inside the LPT module. The results for the estimated assembly times display the trend, that the large number of B-parts accounts for a large amount of the assembly time compared to fewer but heavier A-parts.

6 CONCLUSION AND FUTURE WORK

The method introduced in this work displays a systematic evaluation of assemblability of LPT modules with limited knowledge during Preliminary Design based on a digital model of the concept. Mounting and dismounting paths for axial symmetrical as well as unsymmetrical components can be evaluated in a simplified fully parametric 3D CAD model. These findings aid the set up of an assembly precedence graph, which illustrates the sequence of the tasks to assemble the considered concept. This is complemented by an estimation of the required manual assembly time utilizing the MTM method. The results of two evaluation iterations display a significant dependency of B-parts such as fasteners and seal plates on the assembly time, whereas the quantities of A-parts such as blades have little influence on the assembly time.

In future work, the parametric 3D model will be enhanced to depict more design characteristics for LPT modules. Furthermore, the possibility of a rule based generation of the quantities for fasteners, blades, vane segments, etc. will be evaluated. Additionally, the results of the MTM method will be validated for typical work steps of aero engine assembly.

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