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# An Aircraft Design for Maintainability Methodology Integrated with Computer Aided Design

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**Abstract**
Maintenance typically represents 10 – 25% of the direct operating cost of an aircraft and minimizing maintenance cost is therefore an important driver for aircraft design. This paper presents a methodology for Design for Maintainability that uses an accessibility checklist for maintainability assessment at the preliminary design stage, and a maintenance task time prediction method that can be used at the detailed design stage. Both elements of the methodology use Computer Aided Design to assess virtual maintenance operations for accessibility and human performance. The methodology provides a basis for the comparison of design alternatives with respect to maintainability.

**Keywords**:
Aircraft Design, Maintainability, Computer Aided Design, Maynard Operation Sequence Technique (MOST), Task Time

## 1 INTRODUCTION

Aircraft are highly complex systems that have a service life of 30 or more years and require a high level of operational availability to meet their customers' needs. Regular maintenance is therefore essential to ensure continuing safe operation through this extended lifecycle. Maintenance costs typically represent 10 – 25% of the direct operating cost of an aircraft [1]. Furthermore, the recent trend towards availability contracts means that there can be financial penalties associated with maintenance failures and the need to manage maintenance costs has further increased [2]. Minimizing maintenance cost is therefore an important driver for aircraft design.

This paper presents a design for maintainability methodology that can be applied by design engineers as part of their design activity. The methodology integrates virtual maintenance simulation in a CAD environment with a maintenance task time assessment based on the Maynard Operation Sequence Technique (MOST).

## 2 LITERATURE REVIEW

MIL-HDBK-470a [3] defines maintainability as "the relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair." Put more simply it is a design characteristic that concerns the relative ease and cost of preventing failures or correcting failures through maintenance actions. Maintainability is usually assessed through quantitative measures such as mean time to repair (MTTR) and Mean Time Between Failure (MTBF). Design for Maintainability aims to minimise maintenance costs by considering the maintainability requirements from early in the design process. Physical features that affect maintainability are accessibility, visibility, testability, complexity, interchangeability, identification and labelling, verification and simplicity [4]. Design for maintainability is most particularly relevant for systems with a low MTBF because these systems are frequently maintained and maintenance will therefore be a significant cost factor.

Design engineers currently follow general maintainability design guidelines (for example MIL-HDBK-470a [3]) but do not have tools to assess the maintainability of alternative design concepts. Detailed maintainability prediction is usually undertaken by specialist maintainability engineers, often after later in the design process when it is expensive to make design changes.

MIL-HDBK-472 [5] provides four quantitative maintainability prediction methods based on predicting Mean Time to Repair (MTTR) through empirical methods. These methods facilitate the design, development and early assessments of the maturity of the maintainability design. However, as NASA's Technical Standard for Reliability & Maintainability states, "if applied, the maintainability assessment should be not only an estimate of the Mean Time To Repair for various components of a system, but also a review of the components for crucial maintainability criteria such as accessibility, interchangeability, failure detection, failure isolation, special tools and diagnostics, spares or logistics support sources" [6]. All these factors affect maintainability of a system differently and must be taken into account at early design stages to minimise their adverse effects. "It is usually necessary to change the manufacturing process to incorporate these design changes and if the changes are critical enough, the units already manufactured must be retrofitted to comply with the new design" [7].

MIL-STD-470a [3] and MIL-STD-1472f [8] also establish human engineering design criteria for military systems, equipment and facilities. Maintainability principles and practices are applied in the design of the systems to achieve acceptable performance by maintenance personnel and minimize skill requirements and training time.

CAD tools are extensively employed in the aircraft design process and are increasingly being applied in design for maintainability and ergonomics. The US Air force Design Evaluation for Personnel and Human Factors (DEPTH) program [9] developed a versatile, computer graphics-based human modelling technology to integrate engineering analyses and requirements such as those in the military standards (MIL-HDBK-470/471/472) to illustrate, evaluate, predict and describe interactions between product and human throughout life cycle. Based on the DEPTH program, Abshire and Barron [10], reported how Lockheed Martin's F-16 Program met the technical maintainability target set in 1995 using digital mock-ups to assess maintenance operations, and the benefits obtained thanks to their approach to Virtual Maintenance. Although the simulated results matched closely the real world task with a high level of confidence, a quantitative method for time estimation of maintenance tasks was not found and human performance in maintenance tasks was validated qualitatively. More recently Mavrikios [11] presented an approach to maintainability analysis based on a human-oriented paradigm within a virtual environment in which a scalable digital manikin acts according to the motion captured from a real human operator. Liu et al [12] presented a method for human factors analysis in maintainability evaluation during the design process of a product using virtual reality. The process is divided into three major parts including (1) The objects, environment and task models, (2) the repair simulation in VR based environment and lastly (3) the human factors evaluation and recommendations for improvements. However, these methodologies do not consider maintenance time, or disassembly sequence planning.

Previous research has therefore focussed either on the use of quantitative maintainability assessment methods or the use of 3D computer aided design to simulate maintenance tasks. This research aims to combine the two approaches so that a quantitative assessment method can be linked to a 3D CAD model.

## 3 METHODOLOGY

The methodology presented in this paper can be used by aircraft design engineers to assess maintainability at the design stage. It is intended to facilitate design trade-offs early in the design process when changes can be made at lower cost. The methodology uses CAD based methods for virtual maintainability assessment, combined with accessibility assessment checklists. The methodology has been developed in two stages: the first stage is an accessibility assessment considering safety, accessibility and visibility using a checklist and scoring system. The second stage evaluates maintenance task time including disassembly sequence planning and task time estimation to provide a more detailed maintainability analysis of the design. The methodology process flow is shown in Figure 1. The design for maintainability methodology is iterative and should be undertaken repeatedly through the design process.

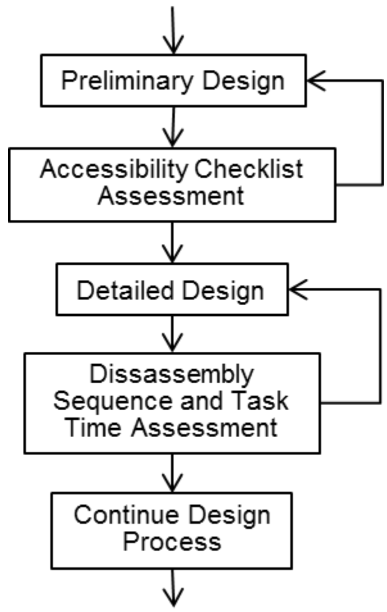



Figure 1: Methodology Process Flow

The prerequisites for applying the design methodology are that the design must be sufficiently mature to allow the preliminary design details for the zone under consideration to be defined. A 3D CAD model of the zone of interest must be available including an external shape envelope of the equipment to be maintained.

### 3.1 Design for Accessibility Checklist

The first stage in the design methodology is a preliminary assessment based on an accessibility checklist. The checklist has been compiled based on maintainability related military handbooks [3,4,8] and ergonomics literature [13,14] and includes elements of safety, design, ergonomics and accessibility. The generic accessibility checklist hierarchy is shown in Figure 2.

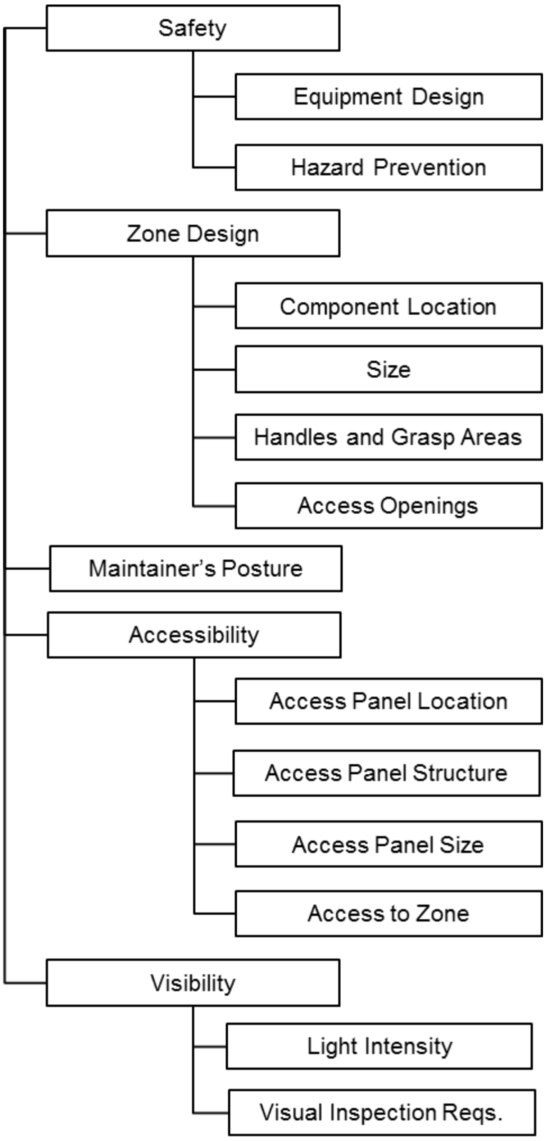



Figure 2: Accessibility Checklist Hierarchy

The first step in applying the process is to populate the hierarchy with all of the maintainability factors that are relevant to the current application. An extract from the checklist for an aircraft avionics bay is shown in table 1. It is important for the designer to consider the full range of factors that may affect accessibility at the start of the process. Each factor is allocated a score value ("1" for compliant and "0" for not-compliant for safety related factors, and a qualitative scale for other factors). Full details can be found in [15].

| **Category/ Sub-Category** | | **Requirement/ Guideline** | **Score** |
|---|---|---|---|
| Safety | Equipment design | Access panels should be free of sharp edges or projections | 0/1 |
| | | There should be handrails on each side of the ladders, stair-ladders and stairs | 0/1 |
| | Hazards prevention | Internal controls should be located away from dangerous voltages or moving parts | 0/1 |
| | | Components retaining heat or electrical charge should be located where maintainers cannot touch them or equipped with bleeder networks | 0/1 |
| Zone Design | Component Location | Does electronic equipment removal not necessitate the removal of other equipment? | 0/1/2 |
| | | How many other components need to be removed to access the component? | 0/1/2 |
| | | Are the most frequently accessed items within convenient reach? | 0/1/2 |

Table 1: Extract from Accessibility Checklist for Avionics bay

In order to evaluate the overall system accessibility rating each factor must be checked for the current system design and a score value assigned. This assessment is performed using a virtual simulation of the maintenance access using 3D manikins in CAD software. A weighted sum of score values is used to calculate the overall accessibility rating of the design. The output of the process is a percentage score representing the accessibility of the system compared to that of the "ideal" system design defined as a system with the maximum score for all factors. This rating can be used as the basis for trade studies between design alternatives or to identify areas that should be considered for design improvements.

### 3.2 Disassembly Sequence and Maintenance Task Time

The second element of the methodology estimates maintenance task time based on disassembly planning. The ability of a system to be maintained is very closely related to its ease of disassembly when accessing a failed component. Two main elements determine the maintainability of a system (1) the system design, (2) the operator's working conditions including human labour performance. The maintenance time emerges from the interaction between the system and the maintenance operator.

The methodology predicts maintenance times by establishing the minimum number of tasks required to disassemble a component and breaking down each operation into human elemental motions which can then be used to estimate maintenance times. The methodology has been structured and designed as an iterative process comprising the steps shown in Figure 3.

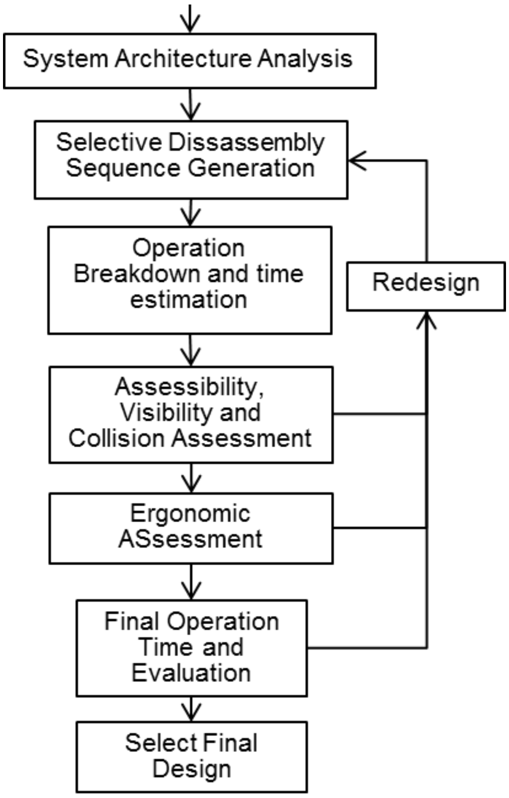
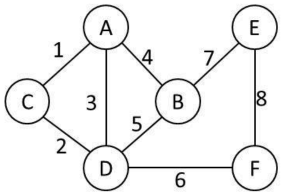



Figure 3: Maintainability Assessment Process Flow

### 3.3 Disassembly Sequence Planning

The first step in the time estimation process is to determine the sequence of disassembly for the part to be maintained. This has been undertaken following the optimal disassembly sequence planning process proposed by Lambert and Gupta [16]. A disassembly precedence graph is used to represent the components in the product assembly and the connections between them. The nodes in the graph represent the parts in the assembly and the links represent the connections between parts. The graph can then be used to generate all of the possible assembly sequences. In this research the most direct disassembly sequence has been selected, although it is acknowledged that this may not be the quickest sequence. An example disassembly precedence graph is shown in Figure 4




| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| A | - | | | | | |
| B | 1 | - | | | | |
| C | 1 | 0 | - | | | |
| D | 1 | 1 | 1 | - | | |
| E | 0 | 1 | 0 | 0 | - | |
| F | 0 | 0 | 1 | 1 | 0 | - |

Figure 4: Example Disassembly Precedence Graph

### 3.4 Task Time Evaluation

Once the sequence of disassembly has been selected, then the time for disassembly and re-assembly are calculated. The Maynard Operation Sequence Technique (MOST) has been used to calculate the task times. MOST is a high-level predetermined motion time system (PMTS) which is based on Methods Time Measuring (MTM) [17]. MTM are procedures that analyse manual operations and methods by breaking them down into the basic motions required to perform them. A predetermined time standard is assigned to these motions determined by the nature of the motion itself and the conditions under which they are carried out. Some fundamental MTM motions include move, reach, turn, disengage, position, grasp and release. MOST is used to analyse work and to determine the normal time that it would take to perform a particular process /operation. The MOST Procedure Steps are as follows:

1. Break down the operation/process into basic steps/units

2. Analyse the motions in each step/unit by using a standard MOST method sequence

3. Assign indices to the parameters constituting the method sequence for each task

4. Sum up the indices to arrive at a time value for each step/unit

5. Sum up the time values for all the steps/units to arrive at the "normal" time required to perform that operation/process

MOST focuses on work activities that involve the movement of items as the majority of industrial manual work does involve moving objects like parts, products, tools or fasteners from one location to another of the workplace. Once the methodology has been applied to the maintenance operation, the methodology produces a set of task times for each step which can be evaluated in order to identify the areas in which improvements can be accomplished. A typical sequence model for the fastening operation of a screw would be: A6-B6-G3-A0-B2-P3-A0-F2-A0-B2-P3-A0 that comprises "Get the screwdriver" (A6-B6-G3), "Place screwdriver in screw slot" (A0-B2- P3) "Unfasten screw" (A0-F2) and "Put screwdriver back" (A0-B2-P3-A0).

| Assessment | Optimum | Intermediate | Poor |
|---|---|---|---|
| **Accessibility** | Operator Reaches Part | Operator Reaches Part with Tool Tip | Operator DOES NOT reach part |
| **Penalty** | NA | NA | Additional motions |
| **Visibility** | Operator Vision Field covers working area without obstructions | Operator Vision Field covers working area with some obstructions | Operator cannot maintain visual contact while performing task |
| **Penalty** | NA | Investigate for Re-design | Additional operation time (+3seconds) |
| **Clash** | No clash with operator and minimum 90º tool sweep angle for tool | Avoidable clash with operator or Minimum 60º Tool Sweep angle | Less than 60º tool sweep angle |
| **Penalty** | NA | Additional operation time (+4seconds) | Immediate Change |
| **Ergonomic** | Green Postural score | Orange Postural score | Red Postural score |
| **Penalty** | NA | Investigate for Re-design | Immediate Change<br>1.5 factor if both hands required |

Table 2: Adjustment Factors for Maintainability Assessment Criteria

This research extends the MOST task time estimation method to incorporate factors relating to the difficulty of the maintenance task in hand. The accessibility, visibility and ergonomics of each task is assessed, and results are used to weight the MOST task time results. The disassembly sequence and task breakdown are simulated using the CATIA V5 software using 3D CAD models of the product, maintainer (as a manikin) and tools. The simulation checks the reach and vision for each operation, and allows additional moves to be added where necessary. Penalties are added to the calculated task times to adjust them for accessibility constraints. The adjustment factors are shown in Table 2. More detail of the task time estimation process can be found in [18]

## 4 CASE STUDIES

### 4.1 A-8 Avionics Bay

The accessibility checklist methodology was applied to the preliminary design of the maintenance bay for the A-8 which is an advanced turbo-prop 70-seater regional airliner designed by post-graduate students at Cranfield University. In the initial design for the A-8 aircraft the avionics bay was located under the flight deck floor and accessed through a cutout in the flight deck floor. Due to the small size of the aircraft the access to the avionics bay is very difficult as can be seen in Figure 5. Using the avionics bay accessibility checklist the initial design of the avionics bay was assessed achieved a maintainability score of 68 %. This relatively low score was to expected as the bay is small and the ceiling is low so that it is not possible for the maintainer to work fully inside the bay. Furthermore the maintainer has to crouch while working in the bay.

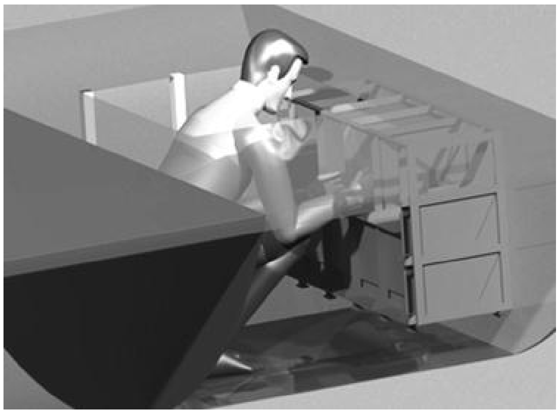


Figure 5: Initial A-8 Avionics Bay Design with 95$^{th}$ Percentile Maintainer

The main weak points identified in the initial design are that there is little workspace clearance, the posture is very uncomfortable for the maintainer, there is a lack of visibility for components at the bottom of the bay, and the components do not have enough handles or grasp areas.

Based on the findings from the initial study an alternative design concept was proposed in which the maintainer accesses the bay from underneath the aircraft. This would allow the maintainer to work in a standing position and would remove many of the accessibility and maintainer comfort problems. The new design is shown in Figure 6. The accessibility checklist process was repeated for the new bay design and achieved a score of 81% demonstrating a significant improvement in access and operator comfort. However, this represents a major design change on the overall aircraft and the impact of this would need to be investigated in detail.

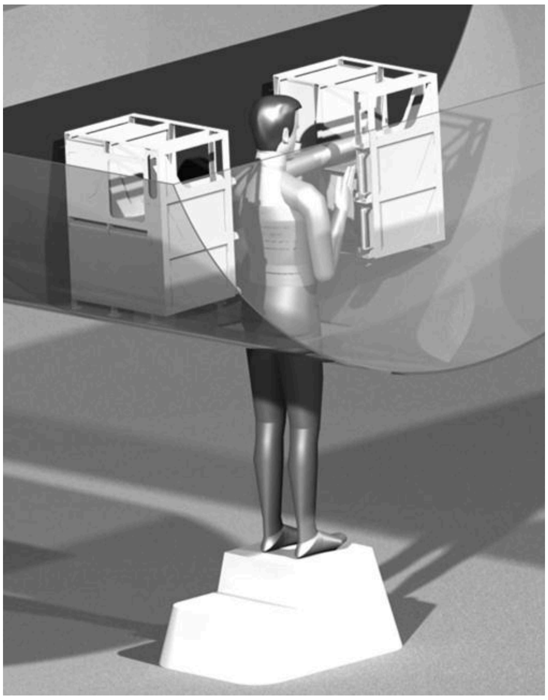


Figure 6: Redesigned A-8 Avionics Bay with 5th Percentile Maintainer.

### 4.2 V-10 rotor system

The second part of the methodology has been applied to the detailed design of the rotor system of the V-10 aircraft. The V-10 is a tilt rotor aircraft designed by students at Cranfield University. The rotor system has a total of 23 components that can be grouped into the following sub-assemblies: the rotor blades, spinner, hub, swashplates, control mechanism, gearbox and mast shaft [19] as shown in Figure 7.

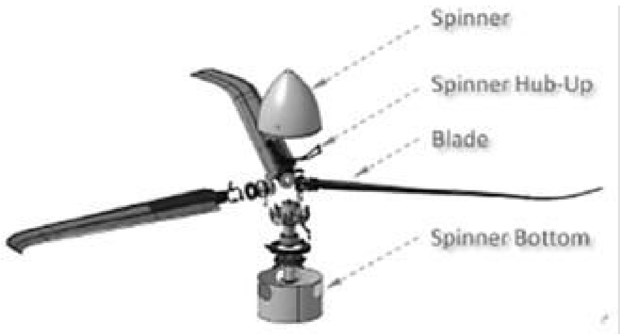



Figure 7: V-10 Rotor System

The first stage in the process was to understand the component assembly for the rotor system and its maintenance procedures. Then a connectivity graph was created from the CATIA assembly model for the system, to define the connectivity between all the parts in the assembly. From this a disassembly precedence matrix could be created and the disassembly sequence for the rotor blade selected. An initial MOST procedure was performance for each disassembly operation with the aid of data from the CAD model. The initial disassembly sequence for the rotor blade is shown in Table 3. Based on the standard MOST assessment the task time for this operation is 3.1 minutes.

| | |
|---|---|
| **Stage 0** | Collect Crane + Reach Crane + Install Crane |
| **Stage 1** | Grasp Screwdriver + Remove Screws + Release Screwdriver |
| **Stage 2** | Move to Crane + Operate to Remove Spinner Top |
| **Stage 3** | Grasp Wrench + Reach for Link Attachment + Remove Link Attachment + Remove Pitch Link Adjustment + Release Wrench |
| **Stage 4** | Reach for Blade + Remove Blade |
| **Stage 5** | Remove Spinner bottom |

Table 3: Initial Disassembly Sequence for Rotor Blade

An accessibility and visibility assessment of the maintenance activities was then performed to assure that visual contact and enough clearance was available for the maintainer. Following this assessment a modification to the initial MOST sequence for the rotor blade removal was required as the accessibility and ergonomic assessment showed that the operators couldn't reach all the screws to remove the spinner (see Figure 8).

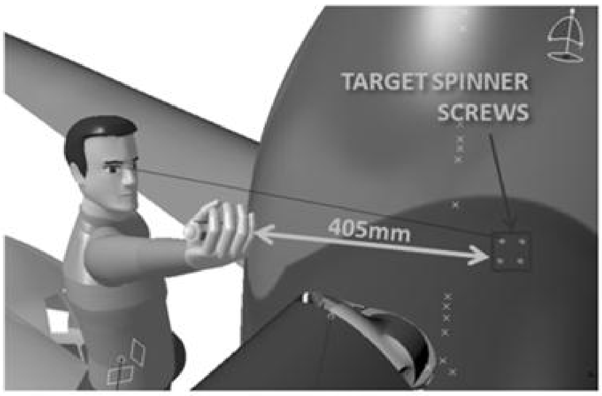



Figure 8: Problem Reaching Screws for Disassembly of Spinner

This accessibility problem led to the need for additional operations in order to rotate the spinner and bring the target screws closer. The grasp, use and release screwdriver operation must be repeated three times and a new operation to rotate the position of rotor was introduced and performed twice. Moreover, certain limitations in the operator's range of movement arose from this analysis, resulting in different levels of accessibility for the manikins.

Ergonomic evaluations (RULA and NIOSH) were performed using CATIA for the most critical postures to guarantee a minimum level of occupational comfort and safety for the operator, using both 5th and 95th percentiles. CATIA's Biomechanics single action analysis conducted for an operator during the extraction of one of the blades from the rotor concluded with a failure to perform the activity for almost 90% of the population. This result indicated that at least two operators using both hands were needed to perform the activity safely and, consequently, a time penalisation factor of 1.5 was applied for the operation. With these additional activities and penalisations for limited range of movement and visibility included, the final activity times were 4.4 and 4.3 minutes respectively for a 5th and 95th percentile maintainer.

Once the maintainability assessment was completed the results were used to redesign the rotor assembly to improve its maintainability. Focussing on the blade disassembly it is clear that a significant proportion of the maintenance time was associated with the use of a crane and the removal of the screws in the spinner hub to access the blades. A breakdown of the disassembly of the rotor blade is shown in Figure 9.

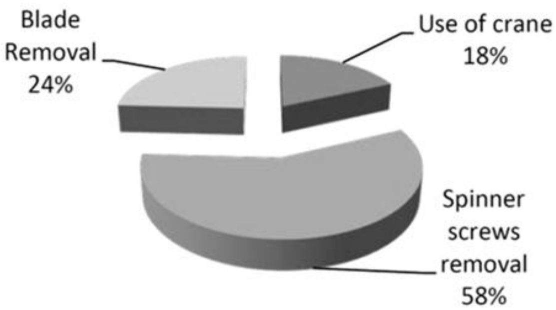



Figure 9: Task Time Distribution for Rotor Blade

A new design is proposed in which a hinge mechanism is added to the spinner and an access panel to allow the blades to be accessed without disassembling the spinner. The new design is shown in figure 10.

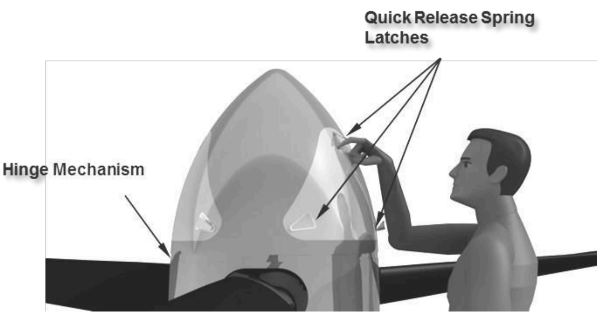



Figure 10: New Spinner Design

The design for maintainability methodology was applied to the new design and new task times were obtained. The time taken to remove a single blade was reduced to 1.5 minutes for a 5th Percentile maintainer, and 1.4 minutes for a 95th Percentile representing a 68% reduction in task time.

The proposed redesign not only reduces the unfastening operation index from a value of 26 to 5 and the number of fasteners from 4 to 3, which results in a reduction from 51.8 to 6.5 seconds for the operation, but also removes the unnecessary turns of rotor to dismantle the screws out of the operator's reach.

## 5 DISCUSSION AND CONCLUSIONS

This paper has presented a design for maintainability methodology that combines an accessibility checklist with virtual maintenance simulation and task time assessment. The methodology has been successfully tested on aircraft system designs and the results used to redesign the systems with substantially improved maintainability. The accessibility checklist provides a simple way to ensure that the designer considers a wide range of accessibility factors in their design. The virtual maintenance simulation in CAD provides the designer with a much greater understanding of the feasibility of accessing and maintaining the system. The task time analysis provides a detailed quantitative assessment of maintenance time, which is more appropriate at the detailed design stage. Both elements of the methodology can be used as a basis for comparing different design alternatives. The case studies have demonstrated the importance of investigating maintainability early in the design process when it is still possible to make major changes to the design.

The main difficulty found in applying the method is the time taken to perform the assessment. The use of manikins in CATIA to define maintenance postures and assess worked comfort is extremely time consuming; it also requires a high level of expertise with design tools such as CATIA v5 and requires the design to be relatively mature in order to be able perform the various simulations and analyses. It is therefore very important to focus design effort on the systems where frequent maintenance access will be required.

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