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Applying Design for Assembly Principles in Computer Aided Design to Make Small Changes that Improve the Efficiency of Manual Aircraft Systems Installations

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ABSTRACT

The installation of essential systems into aircraft wings involves numerous labour-intensive processes. Many human operators are required to perform complex manual tasks over long periods of time in very challenging physical positions due to the limited access and confined space. This level of human activity in poor ergonomic conditions directly impacts on speed and quality of production but also, in the longer term, can cause costly human resource problems from operators' cumulative development of musculoskeletal injuries. These problems are exacerbated in areas of the wing which house multiple systems components because the volume of manual work and number of operators is higher but the available space is reduced.

To improve the efficiency of manual work processes which cannot yet be automated we therefore need to consider how we might redesign systems installations in the enclosed wing environment to better enable operator access and reduce production time.

This paper describes a recent study that applied design for assembly and maintainability principles and CATIA v5 computer aided design software to identify small design changes for wing systems installation tasks. Results show positive impacts for ergonomics, production time and cost, and maintainability, whilst accounting for aircraft performance and machining capabilities.

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INTRODUCTION

Aircraft system installation is still largely a manual process due to the complexity of the installation tasks, difficulty of access and relatively low production volumes. However, as the aircraft market increases, the need to investigate ways to reduce the burden on installers becomes more pressing. Whilst the production volumes are increasing it is still not cost effective to automate these processes, and effort therefore needs to be made to minimize the burden on the operators during the manual installation of aircraft systems.

This paper presents an investigation into how design for assembly and maintainability principles can be applied to ease systems installation in aircraft wings. Ergonomic issues associated with the current systems installation process were identified during a field study on the wing assembly line at a high value wing assembly facility. A range of installation issues were identified and the installation processes were simulated and ergonomics evaluated using the Rapid Upper Limb Assessment (RULA) analysis tool in CATIA. Design methods from design for assembly, maintainability and ergonomics were applied to investigate how the manual systems installation process could be improved for a simple design problem. The results are compared and discussed.

LITERATURE REVIEW

Design for Assembly (DFA) has been widely studied and has been applied extensively in industry, particularly for mass production. Boothroyd, Dewhurst and Knight [1] define DFA as "the design of the product for ease of assembly". DFA helps manufacturers to create "world class products with improved quality, lower cost, and with shorter design cycle" by helping them to "understand the costs of production from the earliest stages of the development while at the same time bringing a relentless focus to the part count" [2]. DFA provides a structured approach to assessing the ease of assembly for a product as a basis for redesign.

Maintainability is defined as "the relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition" [3]. Design for Maintainability (DFMt) aims to minimize 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]. DFMt principles are used in this research in order to assess the accessibility factors that are important for systems installation tasks. MIL-HDBK-472 Procedure III [5] provides a quantitative maintainability prediction methodology that was designed to predict maintenance downtime for military ground equipment, but has also been widely applied to other systems maintenance including aircraft systems. This method allows maintainability predictions to be performed at the design stage, and can be used as a basis for comparing the maintainability of design alternatives.

MIL-STD-470a [3] and MIL-STD-1472f [6] 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. Ergonomics guidelines have been produced for engineers [7] but design engineers often lack the time and understanding needed to sufficiently incorporate human factors [8].

Although there has been a paucity of research exploring ergonomics specific to aircraft assembly, wider evidence suggests that poor design for ergonomics is strongly associated with performance errors and quality decrements, particularly for high-demand tasks [9]. Poor consideration of ergonomics in design for assembly also impacts on worker health. Musculoskeletal disorders (MSDs) are far more prevalent in manufacturing than other sectors [10; 11] and the physical strain is exacerbated when tasks are performed in confined spaces [12] and demand force and repetition [13]. Due to these costly impacts on product quality and human performance it is widely recognised that better consideration of ergonomics needs to be integrated into the design of products and processes to optimise human work and output [14; 15; 16]. Computer aided design human modelling tools are now becoming the common technique for predicting and preventing ergonomic risk [17].

METHODOLOGY

The methodology adopted in this paper utilises design for assembly and maintainability principles in combination with Computer Aided Design (CAD) software to investigate small design improvements that could improve the efficiency of manual aircraft system installations. The methodology has been applied to a design problem as the case study in this paper.

Firstly a field study was undertaken to better understand the problems faced by operators installing systems. CATIA v5 was then used to model the system installation environment and the operator so that the postures adopted by operators during system installation could be simulated in CAD. An ergonomic assessment was performed using the RULA analysis function in CATIA v5 Human Activity Analysis Module to assess the operator ergonomics and a number of tasks were identified as candidates for redesign.

One installation task was selected for further assessment and the existing design was assessed using Boothroyd, Dewhurst and Knight's [1] Design for Assembly method and selected items from MIL-HDBK-472 Procedure III for maintainability prediction.

Four possible design solutions were then proposed to improve the assembly efficiency and each design option was assessed using the same design for assembly and maintainability criteria.

FIELD STUDY

The first objective of this research was to select system installation examples for redesign based on current levels of ergonomic and task completion difficulty. To do this a field study was undertaken in a high value aircraft wing assembly facility.

First, in preparation for the field study, a set of unpublished internal reports from prior ergonomic studies at this particular facility were reviewed as these had already found where ergonomic and task completion difficulties occur. This meant it was possible to identify a list of candidate processes suitable for redesign prior to visiting the facility in terms of *location* along the wing and the *type* the problem.

The list of candidate processes then formed the framework for the field study investigation. Systems installation work was observed and operators were interviewed in order to confirm the criticality of ergonomic / task difficulty and to gather further information to help ascertain suitability for redesign. The field study confirmed that physically demanding postures are commonly adopted for partial entry, with operators needing to twist and stretch in stressful physical positions to reach into the wing cavity from seated or standing positions. To complete tasks and alleviate their physical stress operators frequently reposition but this is often not possible - and their stresses are exacerbated - due to surrounding obstructions and congestion from equipment and other operators. The field study also confirmed that due to the limited recess space inside the cavity it is also common for operators to work blindly, by sensory feel alone, or with only head / shoulder entry (Figure 1). As all of these physical challenges impact on operator safety and wellbeing as well as task performance, details of the problem tasks and working postures adopted by operators were recorded.

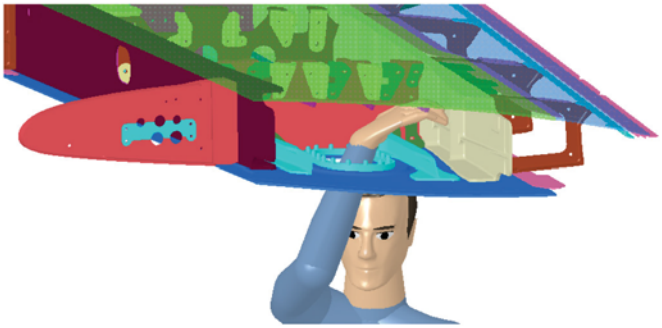

Figure 1. Example posture for wing systems installation tasks.

DESIGN ASSESSMENT

Although a number of candidate process tasks were identified in the field study, this paper will focus on the fuel system sensor bracket and cable installation. Design for assembly and maintainability principles were applied to assess the current designs with regards to assembly, design and ergonomics.

The subject of the design study is the installation of the fuel system sensor cable supports which are required for routing the cables for fuel quantity indicator probes, overflow sensors and temperature sensors in the fuel tanks. These systems contain many components, support brackets and associated cabling that must be manually installed inside the fuel tanks. For example the Boeing 777 has 17 fuel quantity indicator probes per main wing tank, and 5 on each side of the centre tank [18]. The location of the fuel probes is carefully chosen so that the effects of aircraft pitch and roll attitude changes are minimised as far as quantity measurement is concerned [18]. In the current design each support bracket is fastened to the wing rib using two fasteners, after the wing box has been closed and the sensor cables are attached to support brackets using cable-ties. The design rationale for using cable-ties is that they “provide a secure and non-aggressive fixing for wires and harnesses and guide them safely around the structure, pipework, panels and adjoining harnesses.” [19], however, the field study found that cable-tie installation is not easy in a confined space. An example support bracket and cable installation is shown in Figure 2.

Figure 2. Bracket and cable installation existing design.

The following sections provide a detailed assessment of the current design considering the bracket installation and the installation of the cable onto the bracket.

Design for Assembly Assessment

A DFA assessment was undertaken for the current design following the methodology presented by Boothroyd, Dewhurst and Knight [1] to determine the theoretical minimum part count for a sensor support assembly. The current design has 6 parts (rib, bracket, 2 × fasteners, cable tie and cable). The theoretical minimum part count for this assembly based on the DFA criteria defined in [1] (listed in Appendix A) is 2 (the rib and cable are the only essential parts). All other parts could be theoretically redesigned to be integrated onto the rib. It should be noted that the DFA method provides only a theoretical minimum part count as a design aid and this may not be practical for the actual product design.

A further design assessment was performed using other design for assembly guidelines collated from [1] and summarised in Appendix B. The findings for the current design are:

DFA-1: The bracket acts only as a link between the cable and the rib and should be eliminated if possible

DFA-2: Access for assembly operations is restricted due to the confined space in the closed wing. DFA principles recommend avoiding restricted operations if possible

DFA-3: The cable tie requires adjustment during assembly, which is not desirable from a DFA perspective

DFA-4: The bracket location is under-constrained during assembly and the bracket must be aligned with the fastener holes by the operator before it can be fastened to the rib

DFA-5: The installation of the bracket requires two hands - one to hold the part down and the other to insert the fasteners.

The DFA assessment has identified that based on DFA principles the current design is far from optimal. There are four parts in the assembly that could theoretically be eliminated, the parts must be held in position and adjusted during assembly; accessibility is also poor.

Design for Maintainability Assessment

Selected physical design factors from MIL-HBK-472 procedure III checklist A were used to assess the design of the sensor support bracket assembly with regards to accessibility. Checklist A of MIL-HDBK-472 Procedure III uses a total of 15 criteria to assess physical design factors relating to maintainability and five relevant criteria were selected to assess the accessibility of the systems installation task (a list of the selected criteria used is presented in Appendix C). The design was assessed against each factor using a qualitative score from 4 (easy to maintain) to 0 (difficult to maintain).

Based on the five selected assessment criteria, the best achievable score (easiest to maintain) is 20, and the lowest score (least maintainable) is 0. The scores were assessed based on the findings from the field study and the CATIA simulations. The results are presented in Table 1.

Table 1. Design assessment for the existing support bracket assembly using selected checklist items from MIL-HDBK-472 Procedure III checklist A.

	Design Factor	Design Assessment	Score
1	Access (external). Is external Access adequate for visual inspection and manipulative actions?	External access not adequate for visual or manipulative tasks	0
2	Latches and Fasteners (Internal): Determines if the internal screws, clips, fasteners or latches within the unit require special tools	Internal fasteners are not captive, need tools, and require multiple turns for installation	0
3	Access (Internal). Is internal Access adequate for visual inspection and manipulative actions?	Internal access not adequate for visual or manipulative tasks	0
4	Adjustments. Determines if adjustments such as tuning and alignment are required, after a maintenance actions	A few adjustments, but no major realignments are required	2
5	Safety (Personnel). Determines if the maintenance action requires personnel to work under hazardous conditions	Some delay due to precautions taken	2
		Total (4/20)	20 %

Based on the above assessment, the existing design is not ideal from a maintainability perspective. Access to the installation is poor for both visual and manipulative actions, parts need adjustment after installation, and time is consumed due to the confined space and poor access inside the closed wing.

Ergonomics Assessment

The difficult postures that were identified during the field study in relation to fuel system sensor bracket and cable installation were modelled in CATIA v5. Figure 3 shows an example of one posture; here the operator has limited access and visibility through the manhole and is likely to need to rise up (and down) from the chair in order to reach the task. This posture places strain on the arms, neck, shoulders and back and, over time, is likely to lead to the development of musculoskeletal disorders (MSD). It requires regular recovery time, particularly when using heavy tools, fitting heavy components or components that are difficult to insert.

Ergonomic assessments of the postures were made using the 'Rapid Upper Limb Analysis' (RULA) function of CATIA's Human Activity Analysis module. RULA is used to determine the MSD risk of a posture (observed during task performance) based on neck, trunk and upper limb biomechanical loading scores. Body segments are scored individually and then combined to produce final overall scores which indicate criticality in an ascending scale: 1-2 indicates negligible risk, 3-4 low risk, 4-5 medium risk, and 6-7 indicates very high risk that requires immediate change [7]. To illustrate, the individual body segment scores and final RULA scores calculated in CATIA for the posture shown in Figure 3 are shown in Table 2. The second column in the table shows the maximum score that could be obtained for this segment with the RULA method, the third column shows the results for the left body segments and the fourth column for the right body segments. The results show that operators who need to adopt this posture have a medium risk of developing a MSD in the right upper arm and a high risk of MSD in the neck.

Figure 3. CATIA simulation of example posture adopted by operators during assembly task close to the man-hole.

Table 2. Rapid Upper Limb Analysis results for example posture.

Body Segment		Left Side	Right Side
Upper Arm	/6	1	5
Forearm	/3	1	1
Wrist	/4	1	3
Wrist twist	/2	1	1
Posture Score A	**/9**	**1**	**5**
Neck	/6	6	6
Leg	/2	1	1
Trunk	/6	1	1
Posture Score B	**/9**	**8**	**8**

DESIGN STUDY

Four possible design changes have been investigated to ease the installation of the fuel system sensor cables, building on the findings from the design assessments above. The four concepts investigated are:

1. **Install the bracket before the wing is closed**. This design option aims to reduce the time spent by operators inside the wing by installing the brackets onto the ribs before the wing is closed. Postures analysis showed that all postures adopted by operators inside the wing put high strain on the body.
2. **Machine the brackets as part of the rib**. DFA principles aim to reduce part count to save time and effort in assembly. In this design option the ribs are redesigned to incorporate integrally machined brackets eliminating the need to install the brackets during system installation.
3. **Redesign the rib and bracket for easier installation using kinematic principles.** DFA principles recommend designing parts so that they are self-locating and do not need to be positioned by the operator. This design option redesigns the rib and bracket to ensure that the

bracket can be located by design features without manual alignment.

4. **Redesign the bracket to ease the installation of the cables**. Following DFA principles to reduce part count, design options to install the cables without the need for cable-ties are investigated.

The four design options are described below:

Option 1. Install the Bracket Before the Wing is Closed

The system installation task could be eased by installing the brackets onto the wing ribs before the wing box is closed. This task could be performed at the same time as other assembly tasks such as assembly of the rib-feet or installation of the flaps tracks. The benefits of this approach are that no design changes are required and the operator ergonomics/visibility and accessibility for bracket installation are greatly improved. However, the potential disadvantage is the risk of damaging the brackets after they have been installed and increased complexity of the earlier assembly stages. The cables and cable ties will still need to be installed in the confined space after the wing is closed, giving limited benefit to the operators. A comparison between the postures adopted by the operator with the wing closed and open are shown in Figure 4.

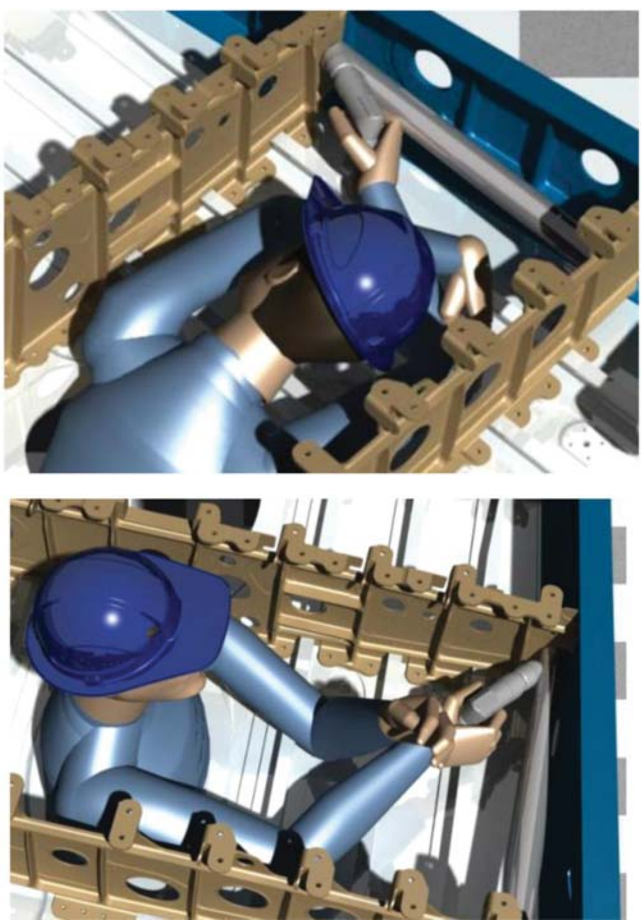

Figure 4. Installation of systems in closed and open Wing.

A RULA analysis was performed using CATIA V5 to compare the operator's posture for a systems installation task in a closed (4 sided) and open (3-sided) wing. The results show that the strain on the operator is significantly reduced if the wing is open (Figure 5).

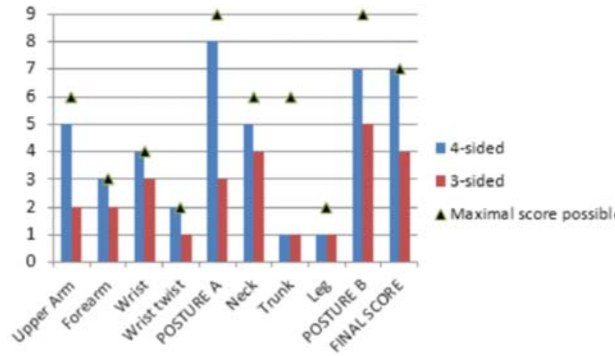

Figure 5. Comparison of RULA analysis for installation with wing box closed and open.

Option 2. Machine the Brackets as Part of the Rib

Following a DFA philosophy, the part count for the support bracket assembly can be reduced by machining the brackets as an integral part of the rib as shown in Figure 6. Two fasteners are also eliminated from the assembly by producing the rib and bracket as a single part. The cost overhead for this additional manufacturing step would be relatively low, but as with option 1, the cable-ties would need to be installed after the wing is closed.

Figure 6. Integrally machined bracket

Option 3. Redesign the Rib and Bracket for Easier Installation using Kinematic Principles

The number of fasteners could be reduced by following determinate assembly principles. Determinate assembly describes the practice “of designing parts, which fit together at a pre-defined interface, and do not require setting gauges or other complex measurements and adjustments' [20]. Figure 7 shows an example of how the bracket and rib could be designed for determinate assembly. In this design, two pads are machined as part of the rib to reduce the number of degrees of freedom during bracket assembly to one. A single fastener is necessary to maintain the part in position. This design option still uses cable-ties but reduces the number of fasteners compared to the current bracket design, and eases assembly due to the easy part location.

Figure 7. Determinate bracket assembly using pad features on rib to locate bracket.

Option 4. Redesign the Bracket for Easier Cable Installation

Following a DFMt philosophy the installation of the cables could be eased by changing the cable attachment method. According to maintainability principles cable ties are not optimal because they require two hands for installation and the tie must be adjusted after installation. Three alternative design options for cable installation were considered: a custom cable guide, bridle rings and snap-in clips as shown in Figure 8. All of these options also offer the potential to reduce part-count by removing the need for a separate support bracket and cable tie.

Figure 8. Concepts for alternative cable supports (custom cable guide, bridle ring, snap-in clip).

Snap-in clips were selected as the best design option because they are a widely available standard part, can be installed directly onto the rib using a single fastener and provide a simple means of cable attachment that will hold the cable securely.

RESULTS

The four sensor cable support design concepts have been compared using the previously described design for assembly and maintainability criteria. The results are shown in Table 3 (refer to Appendix C for scoring criteria).

The results of the design study show that the minimum part count is achieved by machining the bracket as part of the rib (Option 2), however this option still uses a cable-tie, which is difficult to manipulate during installation. The snap-in clip solution (Option 4) allows for easier cable installation, but still requires a fastener to attach the clip to the rib in the confined wing space.

Table 3. Comparison of part count and maintainability scores for different design options.

	Original Design	Option 1	Option 2	Option 3	Option 4	Combined 1,3 and 4
DFA						
Part Count	**6**	**6**	**3**	**5**	**4**	**4**
Maintainability Design Factors						
Access (External).	0	2	0	0	0	2
Latches and Fasteners (Internal)	0	0	2	2	2	2
Access (Internal).	0	2	2	0	0	2
Adjustments.	2	2	2	2	4	4
Safety (Personnel).	2	4	2	2	2	4
% score	**20%**	**50%**	**40%**	**30%**	**40%**	**70%**

Combining options 1, 3 and 4 gives the best overall solution from a design for assembly and maintainability perspective (Figure 9). Support features could be machined onto the rib to allow the snap-in clip to be easily located during assembly. Ideally this operation would be performed while the wing is still open. The use of snap-in clips minimizes the time taken to install the cables in the confined closed wing environment.

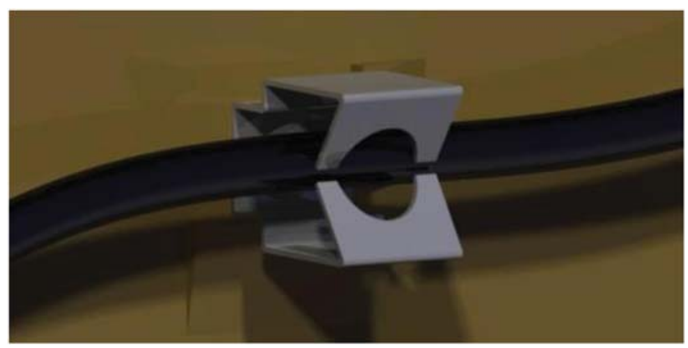

Figure 9. Snap-in clip cable installation design with support features for determinate assembly

This proposed design change has the potential to reduce overall systems installation time and the strain on the operators. Although the time saved for each bracket and cable installation is small, this would become significant when multiplied by the number of sensor brackets per wing and the number of wings produced each year. The potential disadvantages of this design option are the risk of damage to the snap-in clips after they have been installed onto the wing and the need to redesign the ribs for snap-in clip installation, hence this approach is more appropriate for future aircraft than those currently in production.

SUMMARY/CONCLUSIONS

This paper has presented a methodology to investigate small design changes that can improve the efficiency of manual aircraft systems installations and applied it to a simple case study. The research has utilized design principles from ergonomics, assembly and maintenance to perform an assessment of the existing design and installation tasks and then proposed and assessed new design concepts to ease the assembly task.

The ergonomic assessment was performed using a CATIA simulation of the postures adopted by the operators during systems installation tasks. A potential limitation of the research is that the CATIA simulation was created from hand drawn sketches created during observation of the operators because photography was not permitted in the assembly line and is therefore not based on the true measurements. Furthermore, the RULA function in CATIA is limited as it only focuses on the upper body / limb loadings and does not consider the leg stress of the operator, which is an important factor for this application. A more comprehensive analysis could be performed using the REBA (Rapid Entire Body Analysis) technique. Another limitation of the current research is that the physical loads and repetition / duration were not considered.

The proposed design assessment provides a structured approach to generating and assessing design options. The use of CAD simulations aids the visualization and assessment of design alternatives, and allows the assembly tasks to be quickly simulated to compare of design options. A possible limitation of the design study is that although a wide range of design factors were considered, the installation time for each design concept was not assessed.

Two areas of future work have been identified that would improve the accuracy of the presented approach. Firstly, a more accurate ergonomic assessment could be achieved by using a motion capture suit to capture the operator postures, instead of modelling the postures in CATIA from hand drawn sketches. This would allow the actual postures adopted by the operator to be assessed within the software. Secondly, a means to estimate the assembly time within the CAD environment for each design concept would allow for a more accurate comparison between design options.

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DEFINITIONS/ABBREVIATIONS

CAD - Computer Aided Design

DFA - Design for Assembly

DFMt - Design for Maintainability

MSD - Musculoskeletal Disorder

RULA - Rapid Upper Limb Assessment

APPENDIX

APPENDIX A - MINIMUM PART COUNT CRITERIA

Boothroyd, Dewhurst and Knight [1] criteria for minimum part count:

1. During the normal operating mode of the product, the part moves relative to all other parts already assembled. (Small motions do not qualify if they can be obtained through the use of elastic hinges.)
2. The part must be of a different material than, or must be isolated from, all other parts assembled (for insulation, electrical isolation, vibration damping, etc.).
3. The part must be separate from all other assembled parts; otherwise the assembly of parts meeting one of the preceding criteria would be prevented.

The above criteria are to be applied without taking into account general design or service requirements.

APPENDIX B - DESIGN FOR ASSEMBLY GUIDELINES [1]

Identifier	Guideline
DFA-1 Connections	Avoid connections: If the only purpose of a part or assembly is to connect A to B, then try to locate A and B at the same point
DFA-2 Accessibility	Design so that access for assembly operations is not restricted
DFA-3 Adjustments	Avoid adjustments: Design Parts to avoid adjustment during assembly
DFA-4 Kinematic Design	Use kinematic design principles: Avoid over-constraining assemblies, according to kinematic design principles only three point constraints are needed together with closing forces
DFA-5 Part Holding	Avoid, where possible, the necessity for holding parts down to maintain their orientation during manipulation of the subassembly or during the placement of another part. If holding down is required, then try to design so that the part is secured as soon as possible after it has been inserted.

APPENDIX C - MAINTAINABILITY PREDICTION MIL-HDBK-472 [5]

Selected items from Checklist A (maximum score is 4 (easily maintainable) and minimum score is 0 (difficult to maintain))

Design Factor	Description	Score
Access (External). Determines if the external access is adequate for visual inspection and manipulative actions	Access adequate both for visual and manipulative tasks	4
	Access adequate for visual but not manipulative tasks	2
	Access adequate for manipulative but not visual tasks	2
	Access not adequate for visual or manipulative tasks	0
Latches and Fasteners (Internal): Determines if the internal screws, clips, fasteners or latches within the unit require special tools	Internal latches and/or fasteners are captive, need no special tools, and require only a fraction of a turn for release	4
	Internal latches and/or fasteners meet two of the above three criteria	2
	Internal latches and/or fasteners meet one or none of the above three criteria	0
Access (Internal). Determines whether internal access is adequate for visual inspection and manipulative actions	Access adequate both for visual and manipulative tasks	4
	Access adequate for visual but not manipulative tasks	2
	Access adequate for manipulative but not visual tasks	2
	Access not adequate for visual or manipulative tasks	0
Adjustments. Determines if adjustments such as tuning and alignment are required, after a maintenance actions	No adjustments or realignment are necessary to place equipment back into operation	4
	A few adjustments, but no major realignments are required	2
	Many adjustments or major realignments must be made	0
Safety (Personnel). Determines if the maintenance action requires personnel to work under hazardous conditions	Task did not require work to be performed in close proximity to hazardous condition	4
	Some delay encountered because of precautions taken	2
	Considerable time consumed because of hazardous conditions	0