RWTH Aachen University
Institute of Aerospace Systems

The present work was submitted to the Institute of Aerospace Systems

presented by

Jenny Ortmann B.Sc.

Student ID No.: 309334

Master-Thesis

A Methodology for the Quantitative Assessment of the Aircraft Systems Accessibility

Aachen, May 19, 2021

Supervising professor:	Univ.-Prof. Dr.-Ing. Eike Stumpf
Assistant supervisor:	Philipp Hansmann M.Sc. & Lutz Wortmann M.Sc.

1st examiner:	Univ.-Prof. Dr.-Ing. Eike Stumpf
2nd examiner:	Dr.-Ing. Ralf Hörnschemeyer

Zusammenfassung

Aus einer Reduktion des Wartungsaufwandes von Verkehrsflugzeugen aufgrund von Veränderungen in der Systemarchitektur, resultiert die Möglichkeit, die direkten Betriebskosten zu verringern. Am Institut für Luft- und Raumfahrtsysteme wird daher, im Rahmen des AGILE 4.0 Projekts, die Integration von Wartungsaspekten in den Prozess des Flugzeugvorentwurfs erforscht. Die Zugänglichkeit von On-Board-Systemen und deren Komponenten beeinflusst dabei maßgeblich die Wartbarkeit von Verkehrsflugzeugen.

Im Rahmen dieser Arbeit wird eine Methodik zur quantitativen Bewertung der Zugänglichkeit von Flugzeugsystemen entwickelt. Die entwickelte Methodik bewertet 14 unterschiedliche Systemeigenschaften, welche die Wartbarkeit beeinflussen. Um mehrere Abstufungen zwischen Tiefst- und Höchstwert zu ermöglichen, findet die Bewertung auf einer detaillierten Skala statt. Außerdem besteht die Option verschiedenen Wartungsgrößen oder Komponenten durch Gewichtung einen höheren Einfluss auf das Gesamtergebnis zu ermöglichen. Zur Validierung der entwickelten Methodik wird außerdem die etablierte Wartbarkeitsbewertung nach Prozedur III implementiert, welche in Handbuch 472 des US-Militärs veröffentlicht ist. Beide Methodiken werden auf ein Referenzsystem angewandt, welches einem Teil des Hydrauliksystems einer Boeing 777 entspricht.

Die Ergebnisse dieser Arbeit zeigen, dass die selbstentwickelte Methodik eine akkuratere Bewertung der Wartbarkeit ermöglicht. Außerdem berücksichtigt diese auch die Abwägung zwischen gegensätzlichen Systemgrößen. Ein Beispiel dafür ist der reduzierte Bauraum, welcher in Konflikt mit einem größeren Abstand zwischen den Komponenten steht. Des Weiteren wird die Systemanordnung des Referenzsystems hinsichtlich der Wartbarkeitsbewertung beider Methodiken optimiert. Hierbei werden die Vorteile der selbstentwickelten Methodik ebenfalls deutlich, da durch Anwendung der Optimierung bei dieser, im Vergleich zur Prozedur III, eine stärkere Verbesserung der Zugänglichkeit erreicht wird. Die Gewichtungsfaktoren, die in der selbstentwickelten Methodik implementiert sind, ermöglichen es außerdem, gezielt bestimmte Wartungsgrößen zu verbessern. Ebenso kann, durch die komponentenbasierte Gewichtung, gezielt die Wartbarkeit von Komponenten mit höherer Ausfallrate optimiert werden.

Schlagworte: *Masterarbeit, Flugzeugvorentwurf, Zugänglichkeit, Wartung, Wartbarkeit*

Abstract

A reduction of the maintenance effort of commercial aircrafts caused by changes in the system architecture results in the opportunity to decrease the direct operating costs. At the Institute of Aerospace Systems, the integration of maintenance aspects into the preliminary aircraft design is being researched within the framework of the AGILE 4.0 project. Thereby, the accessibility of on-board systems and their components significantly influences the maintainability of commercial aircrafts.

In this thesis, a methodology to quantitatively evaluate the accessibility of aircraft systems is developed. With the self-developed methodology 14 different system properties that influence maintainability are evaluated on a detailed scoring scale, in order to allow gradation between the lowest and highest score. Additionally, there exists the option to use weighting factors to allow different properties or components to have a higher influence on the overall result. To validate the developed methodology, the established maintainability prediction methodology Procedure III, which is published in Handbook 472 of the US military, is also implemented. Both methodologies are applied to a reference system, which corresponds to a part of the hydraulic system of a Boeing 777.

The results of this work show that the self-developed methodology provides a more accurate assessment of the maintainability. In addition, it also takes into account the trade-off between opposing system properties. One example is the restricted installation space, which is in conflict with an increased space between components. Further, the system layout of the reference system is optimized with regard to the maintainability prediction of both methodologies. Here, the advantages of the self-developed methodology also become clear, since a greater improvement in accessibility is achieved, compared to an optimization regarding Procedure III. The weighting factors implemented in the self-developed methodology also allow to target the improvement of certain system properties. Similarly, the component-based weighting can be used to specifically optimize the maintainability of components with higher failure rates.

Keywords: *Master-Thesis, preliminary aircraft design, accessibility, maintenance, maintainability*

Contents

List of Figures

List of Tables

List of Symbols

General Symbols

$\dot{m}$	Mass Flow $[kg/s]$
$\dot{V}$	Volume Flow $[m^3/s]$
A	Area $[cm^2]$
a	Coordinate of Maintenance Access Corner $[cm]$
A_i	Inherent Availability $[-]$
b	Reducing Factor $[-]$
C	Score $[-]$
c	Coordinate of Component Center $[cm]$
d	Diameter $[mm]$
d	Distance $[cm]$
dim	Dimension $[cm]$
e	Function Evaluations $[-]$
F	Factor of BGI582 Endurance Calculation $[-]$
f	Function $[-]$
h_w	Working Height $[cm]$
k_{j1}	Generic Modules Weighting Factor $[-]$
k_{j2}	Fault Isolation Weighting Factor $[-]$
k_{j3}	Maintainability Design Characteristics Weighting Factor $[-]$
k_j	Individual Weighting Factor $[-]$
k_{system}	Total Weighting Factor of the System $[-]$
l	Connection Line Length $[cm]$
l	Tube Length $[m]$
LB	Lower Bound $[cm]$
m	Mass $[kg]$
MCT	Mean Corrective Maintenance Time $[min]$
$MTBF$	Mean Time Between Failure $[FH]$
$MTTR$	Mean Time to Repair $[min]$

N .... Number of Connected Components $[-]$
n .... Total Number of Components $[-]$
$n_{connections}$ .... Number of Connections $[-]$
p .... Pressure $[bar]$
R_{pj} .... Allocated Active Repair Time $[min]$
Re .... Reynolds Number $[-]$
S .... Scoring Factor $[-]$
s .... Steps for Removal $[-]$
UB .... Upper Bound $[cm]$
V .... Volume $[cm^3]$
W .... Weighting Factor of the Self-Developed Procedure $[-]$
w .... Flow Velocity $[m/s]$

Greek Symbols

Δp .... Pressure Loss $[bar]$
δ .... Distance Between Component Centers $[cm]$
$\Delta_{allowed}$ .... Allowed Movement $[cm]$
λ .... Failure Rate $[1/FH]$
λ .... Pipe Friction Coefficient $[-]$
ν .... Kinematic Viscosity $[mm^2/s]$
ρ .... Density $[kg/m^3]$

Subscripts

A .... Checklist A of MIL-HDBK-472 Procedure III
acc .... Accessibility Checklist
$access$ .... Access Characteristic of k_{j3}
$AccSize$ .... Maintenance Access Size
air .... Air
$avlb$ .... Available
B .... Checklist B of MIL-HDBK-472 Procedure III
C .... Checklist C of MIL-HDBK-472 Procedure III
$ConLength$ .... Connection Length
Cu .... Copper
dim .... Dimension of Component or Maintenance Access
$dist$ .... Distance to Maintenance Access

E ... Execution
$electr$ ... Electronic System
fit ... Fit through Access
geo ... Geometry Checklist
$handling$ ... Handling Characteristic of k_{j3}
$hapt$ ... Haptic Access
HF ... Human Factor Checklist
$hydr$ ... Hydraulic System
i ... Component-Dependent Score or Weighting Factor
L ... Load
$mass$ ... Component Mass
max ... Maximum
$NrCon$ ... Number of Connections
obj ... Objective
$occupied$ ... Occupied
$overhead$ ... Overhead Working
P ... Posture
p ... Placeholder for Checklist Name
$pack$ ... Packaging
$pneum$ ... Pneumatic System
pos ... Position of Component or Maintenance Access
$post$ ... Body Posture
$proced$ ... Procedure
$real$ ... Real
$simple$ ... Score for the Simple Approach of MIL-HDBK-472 Procedure III
$size$ ... Component Size
$space$ ... Space Around the Component
$steps$ ... Step-Dependent Score for Checklist C
T ... Time
$total$ ... Total
vis ... Visual Access
$visible$ ... Visible
vol ... Occupied Volume
x ... x-Direction

y	y-Direction
z	z-Direction

Abbreviations

ACMP	AC Motor Pump
ASPAC	Asia Pacific
BC	Boundary Condition
CAD	Computer-Aided Design
DOC	Direct Operating Costs
E	Electronic
FH	Flight Hour
GUI	Graphic User Interface
H	Hydraulic
IATA	International Air Transport Association
LB	Lower Bound
MCT	Mean Corrective Maintenance Time
MENA	Middle East & North Africa
MRO	Maintenance, Repair and Overhaul
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTR	Mean Time to Repair
P	Pneumatic
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment
UB	Upper Bound

1 Introduction

The aviation industry experienced a dynamic change over the last decades. The deregulation of the market opened up the competition between the airlines, which was intensified by the appearance of low cost carriers. This led the established airlines to seek ways to reduce their operating costs [1, p. 223, 24, p. 84-85]. The competition in the aviation industry is further reinforced due to global events from which follow a decrease of demand. For instance, the terrorist attacks of 9/11, the global financial crisis in 2008 or, most recently, the COVID-19 pandemic, resulted in a significant reduction of air traffic [3, p. 317-318, 32, p.4].
The economic pressure and competition leads to a huge interest to reduce the costs in aviation industry. One saving opportunity are the direct operating costs (DOC) of an airliner, which consist of costs for ownership, maintenance and operation, including fees, fuel and the crew [40, p. 2]. The costs for maintenance represent thereby a share of 10-20% of the overall DOC [27, p. 20].
Mainly, there are three options to reduce the maintenance costs. First, the material costs can be decreased by reducing the spare part amount or by opting for different materials. Second, the maintenance intervals can be prolonged, which must be performed considering safety issues. Third and last, the maintenance costs can be decreased by enhancing the system's maintainability. Thereby different domains of the maintainability, for example the accessibility, human factor, component dimensions and the available space can be taken into account. Improving the maintainability is in conflict with the limited space available in an aircraft.

The aim of this thesis is to implement a methodology which allows to quantitatively assess the accessibility of an aircraft system. In order to take into account the airlines' cost reduction requirements at an early stage, the methodology should be suited to be incorporated in the preliminary aircraft design process. Moreover, the methodology is used to optimize the system architecture regarding an augmented accessibility.
The required theoretical principles are provided in chapter 2, where first, the terms maintenance and maintainability are explained in detail. Afterwards, an overview on existing maintainability prediction methodologies is given. Furthermore, a body posture analysis, which is used in the self-developed maintainability prediction, is regarded.

In chapter 3, the implementation of the methodologies, the reference system and the optimization is described. Two methodologies are implemented. First one is Procedure III, which was published in the US Military Handbook 472 [16]. This procedure predicts a mean corrective maintenance time while considering influences of the component design, the need

for additional equipment and the human factor. The predicted maintenance time can also be compared to the allocated maintenance time resulting from Chipchak's maintainability allocation, which constitutes a theoretical maximum value for the predicted time [9].
Second is a new maintainability prediction, developed within the framework this thesis. It considers 14 different system properties that influence the system's geometry, accessibility and the human factor. Further, the trade-off between the restricted installation space and the accessibility is also incorporated. All considered properties are based on system information that is known during the preliminary aircraft design stage.

Finally, the results for both procedures, applied to the reference system, are presented in chapter 4. Additionally, an alternate version of the reference system is also considered, which is modified regarding the limited available space in aircrafts. For both systems, optimizations are performed and the associated results are also presented.

2 State of the Art

This chapter serves to list the fundamentals that are necessary for the understanding of this thesis. After describing the terms maintenance and maintainability, various procedures for predicting and allocating maintainability are discussed. Furthermore the maintainability prediction Procedure III of MIL-HDBK-472 is described in detail, as it is further used in the framework of this thesis. The last topic of this chapter are methodologies to assess the body posture, which is used in the self-developed maintainability prediction.

2.1 Maintenance and Maintainability

2.1.1 Maintenance

Maintenance can generally be defined as 'all actions necessary for retaining an item in or restoring it to a specified condition'. This definition is to be found in the Military Standard 721C entitled '*Definitions of Terms for Reliability and Maintainability*' [17, p. 6]. According to Swanson [46, p. 238], maintenance can be performed using different maintenance policies. The policies, that are dominant in aviation industry are corrective, preventive and predictive maintenance [2, p. 500, 30, p. 1414]. Those are shown in the following figure 2.1.

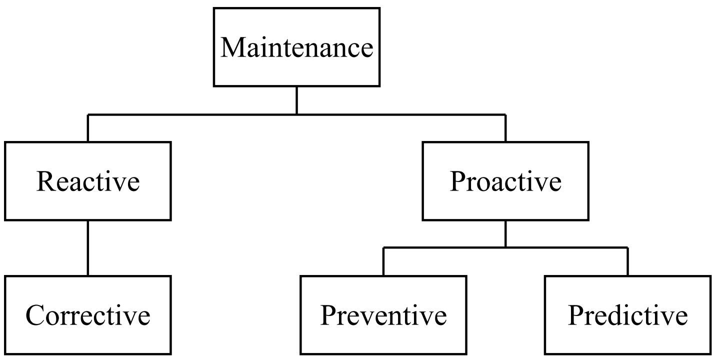


Figure 2.1: Overview and classification of different maintenance policies. Adapted from [48, p. 168] using the vocabulary of [2, p. 500, 30, p. 1414].

Corrective maintenance is a reactive maintenance policy which means that maintenance is performed only as a reaction on the failure of parts. As a consequence, components are used for their complete lifetime, which resulting in lower spare part costs. However, as failures occur mandatorily, corrective maintenance can only be applied to not safety relevant systems, which also do not cause critical damage to other systems if they fail.

In contrast to the corrective policy, **preventive** and **predictive maintenance** are considered as proactive policies. Both have the goal to prevent failures before they occur. The difference between those two strategies is the determination of the time interval in which maintenance is performed. **Preventive maintenance** is the more conservative approach of both, with maintenance being performed at static time or usage intervals, determined by experience, for example a certain amount of flight hour. Common examples are the A-, B-, C- and D-checks. The downside is, that the lifetime of components is not fully utilized resulting in higher costs for spare parts. To make more benefit out of the lifetime of components, **predictive maintenance** aims at more flexible maintenance intervals. This can be achieved by automatically monitoring the systems and predicting the interval using computer-based models and artificial intelligence. As this results in maintenance being performed less frequently, it also follows that the overall maintenance time is reduced. The choice of the most suiting maintenance policy is made individually for each system or component. It always corresponds to a trade-off between safety requirements and cost reduction. This trade-off scenario is qualitatively illustrated in figure 2.2. [48, chap. 5 & 6, 49, p. 1061 ff.]

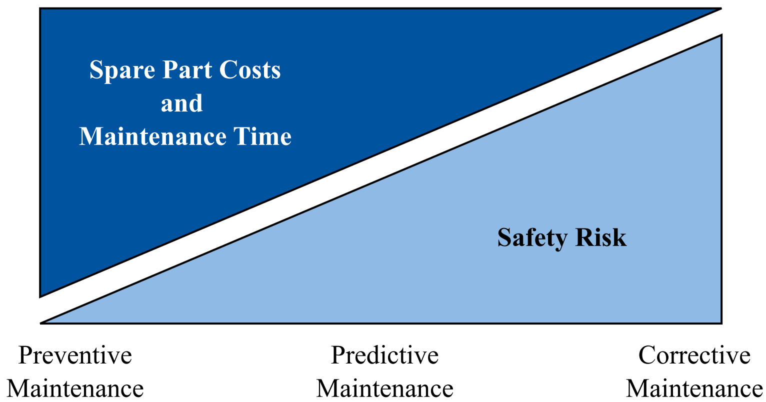


Figure 2.2: Qualitative illustration of the trade-off between maintenance expenses and safety risk depending on the choice of maintenance policy.

As shown in figure 2.3, the direct operating costs (DOC) of a commercial airliner are composed of costs for ownership, for the flight itself and for the maintenance. Thereby, maintenance costs account for 10-20% [27, p. 20] of the total DOC.

More precise data was published in a maintenance cost benchmark analysis by the International Air Transport Association (IATA) in 2019 [29]. It includes data from the *Maintenance Cost Technical Group* (MCTG) consisting of 54 airlines covering 17% of the worldwide fleet [29, p. 18].

As it can be seen in figure 2.4, the regarded airlines and aircraft are distributed over all continents, whereby MENA stands for '*Middle East and North Africa*' and ASPAC for '*Asia*

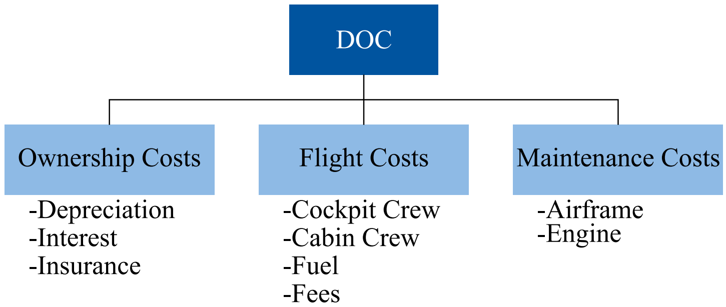
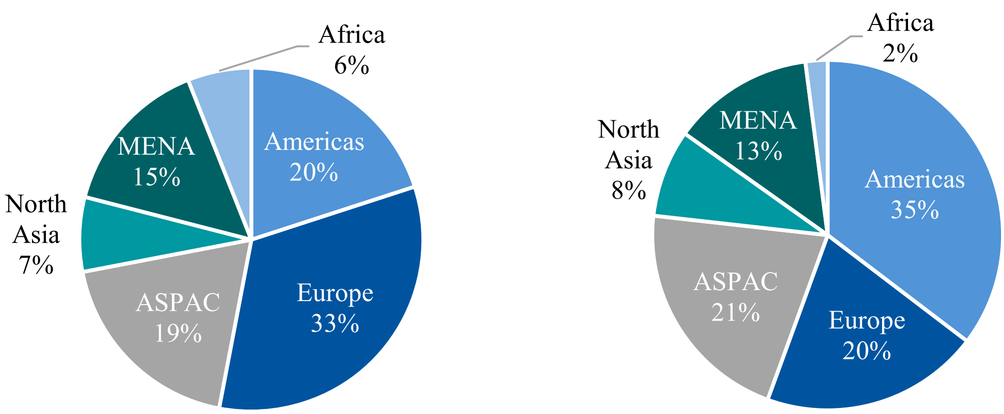


Figure 2.3: Elements of the direct operating costs (DOC) [40, p. 2].

Pacific'. European Airlines represent the biggest share of 33% of all airlines, but only 20% of the observed aircraft. On the contrary, 20% of the airlines are from North and South America but they own 35% of the MCTG fleet.

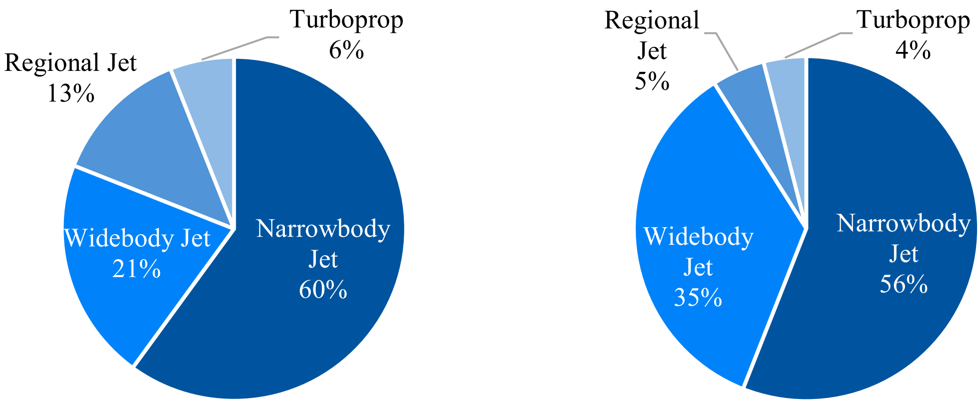


(a) Airlines **(b)** Aircraft

Figure 2.4: Regional distribution of the airlines participating in the MCTG and the corresponding aircraft [29, p. 18].

A comparison of the worldwide and the MCTG fleet is provided in figure 2.5. It can be observed, that narrowbody aircrafts are predominant in both fleets. However, compared to the worldwide fleet, widebody jets are overly represented in the MCTG fleet.

The direct maintenance costs of all 54 airlines combined are $16.49 Billion, which results in an average of $1,089 per flight hour [29, p. 21]. The sum reported by the MCTG represents 24.5% of the worldwide costs for maintenance, repair and overhaul (MRO), while representing only 17% of the worldwide aircraft fleet [29, p. 21]. According to the IATA report, this can be explained by the disproportional high amount of wide-body aircraft in the MCTG fleet. It can be inferred, that there exists an economic interest to facilitate maintenance. In this context, the benchmark analysis also states that the usage of predictive maintenance, also referred to as *health monitoring*, is one of the top three saving opportunities for airlines. The other two being fuel savings and delay reduction. [29]



(a) Worldwide fleet

(b) MCTG fleet

Figure 2.5: Percentage of aircraft types in worldwide fleet (a) compared to the MCTG fleet (b) [29, p. 11, p. 19].

As mentioned before, the use of predictive maintenance can optimize the maintenance intervals. Beside the reduction of spare part costs, a smart scheduling of maintenance can also reduce indirect maintenance costs generated by aircraft downtime [42, p. 10]. But nevertheless, the maintenance task itself remains the same, regardless of the used maintenance interval.

According to Saltoğlu [42, p. 1], the direct costs for scheduled airframe maintenance are mainly composed by costs for labor and material. The IATA benchmark analysis states, that the MRO material costs are increasing [29, p. 15]. On the other side, the use of innovative materials like composites or titanium can reduce the amount of airframe maintenance tasks caused by corrosion or fatigue by up to 60%. This value is found in the *Global Fleet & MRO Market Forecast Commentary* published in 2019 [12, p. 33]. The forecast also highlights, that European and North-American airlines shifted nearly 24% [12, p. 38] of their MRO activities on widebody airframes to China and other Pacific Asian countries, taking advantage of the there existing lower incomes [47] resulting in lower labor costs.

Furthermore, labor costs can also be reduced by lowering the time needed to perform maintenance tasks. This is achieved by incorporating the maintenance aspect into the design decisions made during aircraft development. The properties and design features of a system, which influence its ability to be maintained, are covered under the term '*Maintainability*'.

2.1.2 Maintainability

The definition for *Maintainability* can be found in MIL-STD-721C [17, p. 5] and reads as follows:

> 'The measure of the ability of an item to be retained in or restored to 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.'

Maintainability can also be considered as 'a design parameter intended to minimize repair time' [8, p. 36]. There are multiple design features who have a direct influence on maintainability. For this purpose, several definitions can be found in literature. A comparison of four different sources is shown in table 2.1.

DOD-HDBK-791 [14, p. 1-7]	MIL-HDBK-472 [16, p. 2-2]	Ebeling [22, p. 223]	Tjiparuro [50, p. 107]
Accessibility	Localization	Accessibility	Accessibility
Visibility	Isolation	Modularization	Assemblibility
Testability	Disassembly	Diagnostics	Standardization
Complexity	Interchange	Level of Repair	Simplicity
Interchangeability	Reassembly	Repairing vs. Discarding	Identification
Identification and Labeling	Alignment	Fault Isolation	Diagnosability
Verification	Check Out	Reliability	Modularization
Simplicity		Standardization	Serviceability
		Interchangeability	Testability
			Parts/Components
			Reliability

Table 2.1: Comparison of maintainability design features as found in literature.

In addition to the design features presented in table 2.1, Tjiparuro & Thompson [50] further identified influences of logistic support, operation context and personnel. They depicted the four branches in the 'Maintainability elements cross', which can be seen in figure 2.6. In total, they listed 22 elements having an effect on the mean time to repair (MTTR), the mean time between failure (MTBF) and the choice of maintenance policy.

Maintenance time cannot only be reduced by directly reducing the MTTR, but also globally by increasing the maintenance intervals, which corresponds to a higher mean time between failure (MTBF) or mean time between maintenance (MTBM). The following list gives a more detailed description of certain maintainability elements and their effect on maintainability.

Accessibility Per definition, accessibility is 'a measure of the relative ease of admission to the various areas of an item for the purpose of operation or maintenance' [17, p. 1]. The access to an component can be divided into external and internal access. First is determined by size, structure and location of the access panel. Second includes the location, size and design of the component itself but also the possibilities of reaching said component. This also covers the amount of disassembly needed to access the component. [16, p. 3-33, 31, p. 4]

Assemblibility Assembly and disassembly of a system should be feasible without the need to modify items.

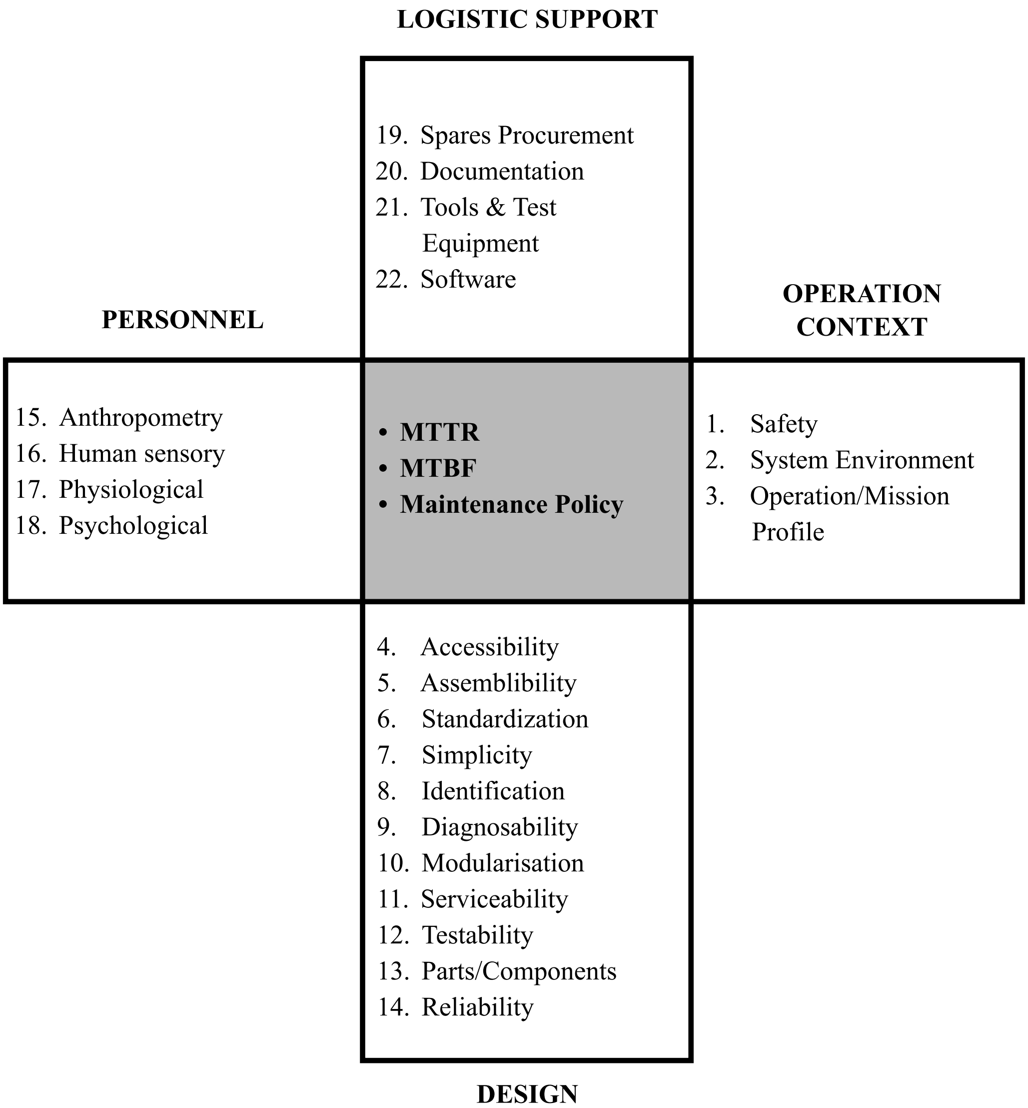


Figure 2.6: Maintainability elements cross by Tjiparuro & Thompson [50, p. 107].

Visibility Describes the ease to get visible access to the component. A good visual access facilitates removal and installation of the component, but it is also important for components requiring visual inspection. [31, p. 4]

Interchangeability The possibility of 'removing the item that is to be replaced, and installing the replacement item' [17, p. 5] is called interchangeability. The enhanced use of standardized items, also referred to as **standardization**, can further improve the interchangeability.

Fault isolation As defined in MIL-STD-721C [17, p. 5], fault isolation is 'the process of determining the location of a fault to the extent necessary to effect repair'.

Testability Considers if the connections and/or displays needed to diagnose the failure of an item are available and reachable. An improved testability, also called diagnosability, therefor also leads to an improved fault isolation. [16, p. 3-39 ff.]

Identification & Labeling Properly labeled components lead to an improved maintainability by avoiding additional research to identify the required component.

Reliability A better reliability leads to a higher MTBF and MTBM, thus resulting in a reduced overall maintenance time [17, p. 7 ff.]. The reliability of the components should also be considered when defining its location. If possible, components that need to be replaced more often should be prioritized for placement in locations with better accessibility.

Modularization Another use of the reliability is to summarize items with similar MTBM into modules. Like this, multiple components can be replaced in one step.

Human Factor Describes the effect of the maintenance task on the performing mechanic. Beside physiological aspects like the lifting mass or the mechanics posture, it also includes psychological aspects like the required degree of concentration or accuracy. [16, p. 3-52 ff.]

Further details on the design decisions affecting simplification, standardization, interchangeability, accessibility, modularization, identification, testability, diagnosability and preventive maintenance can be extracted from checklists provided in DOD-HDBK-791 [14].

2.2 Maintainability Prediction

2.2.1 Procedures of the US-Military

There are several approaches to predict the maintainability of aircraft systems. Most known and used are the five methodologies contained in handbooks 472 and 470A published by the US Department of Defense in 1966 and 1984 respectively. MIL-HDBK-472 [16] comprises Procedure I to IV, while Procedure V is included in Appendix D of MIL-HDBK-470A [15]. A short summary and comparison of the procedures is given below.

Procedure I is used to predict the flight-line maintenance of airborne electric and electromechanical systems. This prediction can only be performed after the design concept has been established. It requires detailed knowledge of the used components and supporting services, for instance precise work schedules of mechanical and operational personnel. [16, p. 1-1 ff.]

Procedure II predicts the corrective and active maintenance time of shipboard and shore electronic or mechanical systems during the final design stage. It is stated, that this procedure can also be applied to similar systems of other branches of the armed services, if sufficient similarity is given. The corrective maintenance (Part A) is predicted using a table containing data from 300 observations of maintenance activities in the US military. On the opposite, the prediction of the active maintenance time (Part B) is based solely on experience. If no experience information data is provided, estimations must be made to assure that the requirements are achieved. [16, p. 2-1 ff.]

Procedure III focuses on the maintainability prediction for electronic system used on the ground, for example radar stations. It is based on the basic principles of random sampling. It only considers corrective maintenance tasks. The resulting mean corrective maintenance time includes the time needed for preparation, fault location & correction, adjustment, calibration and final test of the item. The corresponding evaluation is based on three checklists, taking into account the influence of design, needed facilities and human factors. The design aspect includes the design of the component in terms of mass, size and handling aspects, but also the internal and external accessibility of the system. Contrary to the above presented procedures, this one aims at the design and development stage and can additionally be used as a guidance for making design decisions. [16, p. 3-1 ff.]

Procedure IV is a more general approach, applicable to all systems. It puts the corrective maintenance downtime into relation with scheduled preventive maintenance tasks and relies on expert judgment and experience. To evaluate the resulting downtime detailed information is needed. This includes, among others, system block and flow diagrams, available resources, maintenance concept and a distinct definition of the performed task. The performing analyst needs to add his subjective evaluation concerning maintenance task times to the aforementioned objective data. The accuracy of Procedure IV is therefor dependent on the qualification of the analyst. [16, p. 4-1 ff.]

Procedure V consists of two separate methods: Method A for early prediction and Method B for detailed prediction. Both are applicable to aviation, ground and shipboard electronic systems. Although Method A is aiming at the early design phase it still requires more detailed information than the properties of the components. For instance, the fault isolation strategy and the replacement concept must be known. This prediction method is limited to the consideration of one failure at a time and does not consider visibility or accessibility. [15, p. D-1 ff.]

Beside the previously mentioned individual disadvantages, the age of the procedures should be acknowledged too. Procedure I to IV were published in 1966. And even the latest addition, Procedure V, dates from 1984. Since that time, the aviation industry has evolved considerably [44]. Although the age is not a criterion for exclusion, the resulting maintenance times should be regarded with caution.

Of those procedures, only Procedure III considers the maintainability elements accessibility, visibility and human factors. This procedure was also adapted for more universal usage by Bin Wan Husain [6] in his Ph.D. thesis.

2.2.2 MIL-HDBK-472 Procedure III

Procedure III predicts the downtime caused by the replacement of a defective component. This time is also referred to as *Mean Corrective Maintenance Time* (MCT). To calculate this time, each maintenance task is evaluated and scored using three checklists accounting for aircraft and component design, facilities required to perform the maintenance and the human factor. Each checklist features a different amount of questions, whose answers are scored between 0 and 4. The score 0 equals the lowest score and vice-versa is a score of 4 correspondent to the best result in terms of maintainability. In the following, the original methodology from the US-Military Handbook 472 [16, p. 3-1 ff.] as well as the adaptations of Bin Wan Husain [6, chap. 5] will both be discussed.

The maintainability prediction starts with checklist A, which, as it can be seen in table A.1, features 15 questions. It 'is used to score specific maintenance tasks that are a function of physical design variables such as packaging, access characteristics, test points, displays etc' [16, p. 3-12] and is therefor also called the 'design checklist' in this thesis.

Bin Wan Husain provided an approach to answer questions 2 and 3 of checklist A, which consider the latches and fasteners, depending on the used fastening type, as it can be seen in table A.2. This facilitates the decision-making process by directly linking the fastener types to a score, by using the time needed to loosen or tighten the fastening. For the questions 1 and 4, concerning the internal and external access, Bin Wan Husain provided table A.3, coming from DOD-HDBK-791 [14, p. 4-4], as a decision-making aid. In this table different access types are categorized based on their desirability for physical or visual access. Unfortunately, no scoring was provided by Bin Wan Husain for those considerations.

Table A.4 represents Checklist B, which contains seven questions scoring the need for supplementary facilities dictated by the design. Those can be jigs, external testing equipment, additional personnel or connectors [16, p. 3-12].

The third and last checklist is called Checklist C and 'evaluates the personnel requirements relating to physical, mental and attitude characteristics' [16, p. 3-12]. The following aspects of human factor are considered in the ten questions of checklist C:

C1 - Arm, leg and back strength
C2 - Endurance and energy
C3 - Eye-hand coordination, manual dexterity and neatness
C4 - Visual acuity
C5 - Logical analysis
C6 - Memory: Things and ideas
C7 - Planfulness and resourcefulness
C8 - Alertness, cautiousness and accuracy
C9 - Concentration, persistence and patience
C10 - Initiative and incisiveness

All questions of checklist C are scored in a subjective manner, based on the required effort. Thereby, score 0 stands for maximum effort, 1 for above average, 2 for average, 3 for below average and 4 for minimum effort needed. The individual scoring guidelines are not defined in detail and require the readers interpretation. Furthermore, the resulting scores depend on the individual skill and experience of the performing mechanic. In the following, the scoring guideline for question C5 (Logical Analysis) is given as an example, the remaining guidelines can be found in [16, p. A3-54 ff.].

> **C5 - Logical Analysis** Determines the degree of logical analysis required to complete the maintenance action. Refers to the need for involved logical analysis or for extensive mental reasoning to determine the origin of the fault or malfunction. If the problem is such that it requires orientation on the logical signal sequence, then this shall also be considered as part of this question. [16, p. A3-55]

This example underlines the fact, that the task evaluation in checklist C requires personal interpretation as the guidelines are not defined explicitly enough for an objective scoring. Therefor, Bin Wan Husain implemented an adapted version of Checklist C, which allows a more objective scoring of the human factor. The adapted scoring can be found in table A.5. He referred question 1 (Arm, leg, back strength) to a percentage of human strength and question 2 (Endurance and energy) to standard values for the average maximum lifting load of a male person. Question 7 (Planfulness and resourcefulness) is scored after the number of tools or resources needed, with 2 or less tools corresponding to an ideal score of 4 and 10 or more tools to a score of 0, with a gradation between these two scores. Bin Wan Husain decided to score the remaining seven questions based on the number of steps needed to perform the maintenance task. Here, a score of 0 equals more than 15 steps and a score of 4 equals to 3 or less steps, again with a gradation in between.

After the assessment of all questions has been done, the scores are summarized for each checklist separately. Those total scores are entered in equation 2.1 as terms C_A, C_B and C_C. This results in the predicted corrective maintenance time MCT in minutes [16, p. 3-31].

$$MCT = 10^{(3.54651 - 0.02512 \cdot C_A - 0.03055 \cdot C_B - 0.01093 \cdot C_C)} \tag{2.1}$$

The original procedure from Military Handbook 472 was designed to predict the maintainability of electronic ground systems [16, p. 3-1]. However, Bin Wan Husain validated his adaptation for two different landing gears [16, chap. 7], indicating that the procedure can also be used for aviation and non-electronic systems.

Although this shows, that the procedure is suited to predict the maintainability of aircraft systems, it also has some downsides. The evaluation of the internal access of the components does only consider the relations between different components and the installation space, but it does not include the relations between the components. Also, some system properties, like latches and fasteners, are not yet precisely defined in the preliminary aircraft design. The human factor checklist does not provide an objective scoring of the questions. The adaptation of Bin Wan Husain allows a more objective scoring, but using this, 7 of the 10 scores of checklist C are scored on the removal steps and have therefor identical values. Furthermore, the scoring range between 0 and 4 does not allow an accurate evaluation of the system properties. Some questions also just assign the scores 0, 2 and 4, which intensifies this disadvantage.

2.2.3 Other Procedures

Another maintainability prediction methodology taking into account the accessibility was developed by LOCKETT et al. [31]. It aims at making design decisions based on the maintainability of the system. As shown in figure 2.7, the methodology can be separated into two iterative phases, with a preliminary design as the initial input.

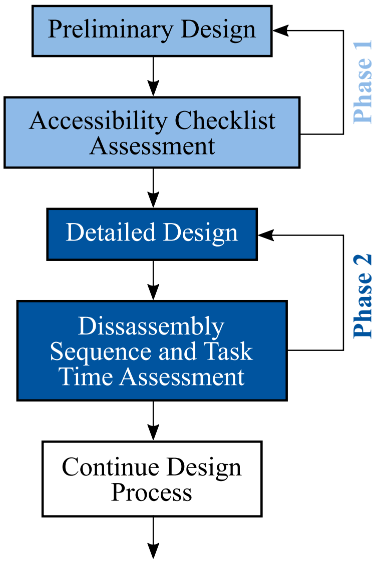


Figure 2.7: Process flow of the maintainability methodology developed by LOCKETT et al. [31, p. 3].

The first phase is applied in the preliminary design stage, with the intention to make early design decisions, resulting in reduced development costs. It considers accessibility aspects, including safety, zone design, visibility and the maintainer's posture by applying a checklist-based scoring system. Each topic is scored between 0 and 2 by answering associated questions. Unfortunately, only an extract of the used checklist is presented in the paper [31, p. 4].

Finally, the individual scores will be summarized into a weighted sum. This will then be put into perspective by comparing it to the maximum achievable score, resulting in a percentage as the final output. The first step can only be performed, if a basic 3D-CAD model of the regarded installation zone, including the outlines of the components, is available. Furthermore, other details, for example handles or inspection requirements, of the preliminary design must be known.

The second phase takes into account the disassembly sequence and maintenance task times and therefor provides a more detailed analysis of the system. It is performed using a 3D-CAD simulation and precise estimations of the time needed to perform every single step of the maintenance task. Therefor, detailed knowledge of the regarded system and its components must be available to perform the second phase of the methodology. The output of the second phase is a detailed evaluation showing how long each maintenance task takes to be performed and in which order the components must be removed. The goal is to find an optimal system architecture regarding the maintenance time and disassembly sequence.

Luo et al. [33] put their focus on layout and spatial accessibility. They take into account the internal access of the components for different access directions but also the space needed for the safe operation of each component. The simulation results show a trade-off between maintainability and the used layout space.

2.3 Maintainability Allocation

The maintainability allocation procedure was published by Chipchak [9] in 1971 and allows to calculate the allocated maintenance time. This time corresponds to a maximum value for the maintenance time predicted by one of the maintainability prediction methodologies presented in chapter 2.2.1. The calculations take into account the reliability and maintainability design characteristics of the component. With the use of field experience, the component characteristics are transformed into weighting factors.

The first step of the maintainability allocation is to assign the weighting factors k_j to each component of the regarded system. Each component has three weighting factors describing its maintainability design characteristics. The first one, k_{j1}, is defined by generic module types. Chipchak only allocated k_{j1} for ground-equipment, shown in table 2.2 on the left side.

Module-List after Chipchak		
No.	Module	k_{j1}
1	Lights	1
2	Digital	1
3	Low-level analogue	1.5
4	High-level analogue	1.5
5	Digital computers	2
6	Power supplies	2
7	Electromechanical equipment	3
8	High-power/high-frequency components	4
9	Interconnections	4
10	Air conditioners	4
11	Liquid coolant systems	4
12	Mechanical structures	6
13	Rotating mechanism/engines	10

Revised Module List after Bin Wan Husain		
No.	Module	k_{j1}
1	Lights	1
2	Digital	1
3	Low-level analogue	1.5
4	High-level analogue	1.5
5	Communications	2
6	Digital computers	2
7	Power supplies (Electrical/Electronical)	2
8	Actuator	3
9	Electromechanical equipment	3
10	Interconnections (Mechanical) - Pipe, valve	3
11	Pump	3.5
12	Air conditioners	4
13	High-power/high-frequency components	4
14	Interconnections (Electrical)	4
15	Liquid coolant systems	4
16	Mechanical structures	6
17	Mechanical structures with mechanism	8
18	Rotating mechanism/engines	10

Table 2.2: Generic modules weighting factor k_{j1} according to Chipchak (left) [9, p. 587] and Bin Wan Husain (right) [6, p. 63].

Bin Wan Husain adapted this table for aviation and non-electronic component types, which can be seen on the right side of table 2.2. He calculated the corresponding k_{j1}-factors based on a correlation between k_{j1} and the maintenance task time as well as the component failure rates. Detailed documentation can be found in [6, p. 64 ff.] or [7].
The second weighting factor, k_{j2}, takes into account the fault isolation technique. As it can be seen in table 2.3, the score depends on whether the fault isolation is performed manually, semi-automatically or automatically.

Fault Isolation Technique	Consideration	k_{j2}
Automatic	Computer or bit circuitry providing automatic fault isolation to replaceable item	0
Semiautomatic	Bit circuitry controlled manually (includes test point selector switch/meter combination)	2
Manual	Manually making measurements using portable test equipment at circuit test points	4

Table 2.3: Fault isolation weighting factor k_{j2} [9, p. 587].

The third and last weighting factor, k_{j3}, considers the component's maintainability design characteristics. The scoring is shown in table 2.4 and it is performed based on considerations taking into account the component's accessibility and handling characteristics.

Maintainability Design Characteristics	kj3	Considerations	
		Accessibility	Handling
Simple	0	Affords direct access, rack mounted	one-man lift and carry
Difficult	2	Involves removal of more than one cover	two-man lift and carry
Very difficult	4	Requires considerable disassembly to reach subject item	hoist-lift,needs dolly for movement

Table 2.4: Maintainability design characteristics weighting factor k_{j3} [9, p. 587].

For each component j, all three weighting factors are summarized according to equation 2.2 to the individual weighting factor k_j, whereby n corresponds to the total number of components. Together with the failure rate λ of each component, the total weighting factor for the system k_{system} can be calculated according to equation 2.3. Finally, with the aid of equation 2.4, the allocated active repair time R_{pj} can be calculated for the regarded component. To perform this calculation, the MTTR must be known.

$$k_j = k_{j1} + k_{j2} + k_{j3} \tag{2.2}$$

$$k_{system} = \frac{\sum_{j=1}^{n} \lambda_j k_j}{\sum_{j=1}^{n} \lambda_j} \tag{2.3}$$

$$R_{pj} = MTTR \cdot \frac{k_j}{k_{system}} \tag{2.4}$$

The MTTR can either be predefined, deducted from the maintainability prediction or calculated based on the MTBF and the inherent availability A_i. For the last approach, the MTBF can be calculated based on the failure rate λ by using equation 2.5. The inherent availability A_i must be predefined. A typical availability requirement is $A_i = 0.9998$ [7, p. 302]. With those two values, the MTTR can eventually be calculated with equation 2.6.

$$MTBF = \frac{1}{\lambda} \tag{2.5}$$

$$MTTR = \frac{MTBF \cdot (1 - A_i)}{A_i} \tag{2.6}$$

2.4 Body Posture Analysis

Different procedures to evaluate the body posture during work tasks can be found in literature. Common examples are, among others, the *Rapid Entire Body Assessment* (REBA) [28, 35] and the *Rapid Upper Limb Assessment* (RULA) [36]. An overview including those and other procedures was given by Cecilia Berlin in [4, p. 144 ff.].

Both, REBA and RULA, are similar to each other and both are suited for the posture analysis of the entire body during static work. They include scores for neck, trunk, legs, arms and wrist while also considering the lifting load. REBA was developed in 1995 and is based on the same scoring tables as RULA, which was presented in 1993. In addition to the features of RULA, REBA further takes into account risk factors for trunk and leg loading, for the presence of handles or other coupling and for dynamic working postures. Because of the extended features and as it is more recent, it was decided to only consider REBA in the further content of this thesis. [28, 35, 36]

The overall work flow of REBA is depicted in figure 2.8. The inputs are colored in dark blue and include the individual posture scores, the load factor and the coupling factor as well as the activity score. The scores A, B and C are determined by tables using the aforementioned inputs. The final score, depicted in green, results from the addition of score C and the activity score. In the following, the procedure is described in detail. The associated tables and figures can be found in appendix A.

First, the postures of neck, trunk and legs are scored according to figure A.1. For the trunk, the position is scored between 1 and 4, depending on the flexion angle. For all body parts, the lowest score corresponds to the best posture in terms of health risk. In this case, the score of 1 is assigned to a person standing upright and the score of 4 is assigned to a forward trunk flexion of more than 60°. For the intermediate scores, forward and backward flexions are considered. The neck posture is also scored based on its the flexion angle, whereby a forward

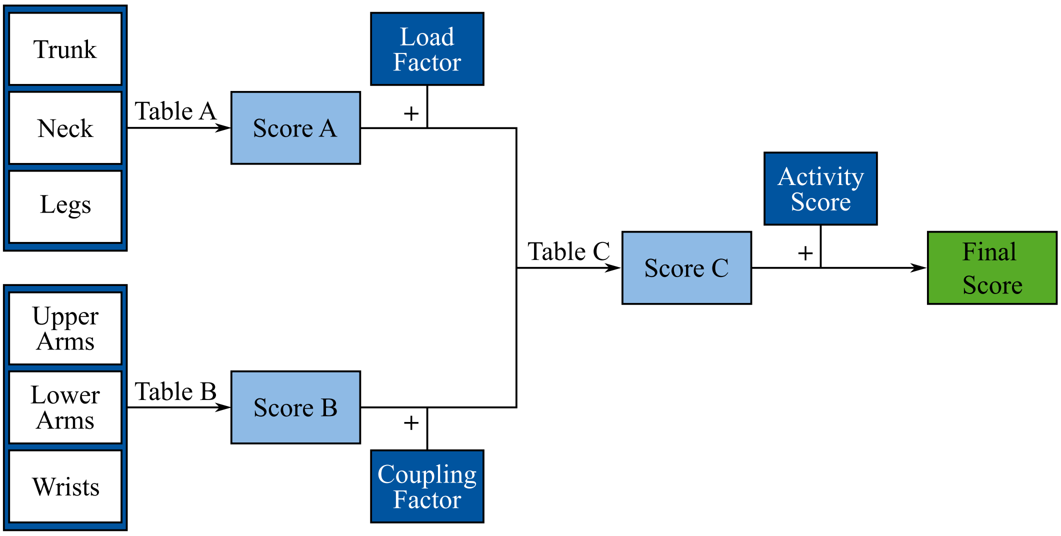


Figure 2.8: Workflow of the REBA procedure [28, p. 203].

flexion up to 20° corresponds to score 1. Larger forward flexions and all backward flexions are scored with 2. Both, the neck and the trunk score, are augmented by 1 if the body part is twisted or flexed to the side. The optimal leg score of 1 can be achieved when both feet are on the ground. An augmentation of 1 or 2 is performed depending on the knee flexion.

The individual scores are combined to score A by using table A.6. The load factor depends on the lifting mass and is defined by table A.7. It has a value of 0, 1 or 2 depending on whether the lifting mass is below $5\,kg$, between $5\,kg$ and $10\,kg$ or above $10\,kg$ respectively. The load factor is additionally augmented by 1 in the case of shock or rapid force build up. The load factor is added to score A.
The calculation of score B considers the individual scores for the positions of wrist, upper and lower arm. Those are assigned as shown in figure A.2. The score for the upper arm equals 1 if the flexion is between 0° and 20° in forward or backward direction. The highest score 4 corresponds to a forward flexion above 90°. The lower arm is scored based on the elbow angle. If the angle is between 60° and 100° the score equals 1. In all other cases it is equal to 2. The wrist score corresponds to 1 if the angle is below 15° and it corresponds to 2 for larger angles. Hereby, the score is augmented by 1 if the wrist is twisted.
Those three scores are transformed into score B by using table A.8. The coupling factor, which is added to score B, takes into account the existing handles and their appearance. It is assigned based on the grading shown in table A.9. The coupling factor corresponds to its best value of 0 when well-fitting handles are provided.

The score C is determined by combining the sum of score A and the load factor with the sum of score B and the coupling factor. This is done by using table A.10.
Afterwards, the activity score is determined. It lies between 0 and 3 points, with one point being added if one or more body parts are static, in the case of repeated small range actions or if the action causes rapid large range changes in posture.

The final REBA score is build by adding the activity score to score C. The evaluation of the body posture is finally performed using table 2.5 which provides the risk level of the posture and the need to perform changes, based on the value of the final REBA score.

REBA Score	Risk	Change
1	Negligible Risk	None
2-3	Low Risk	May be needed
4-7	Medium Risk	Necessary
8-10	High Risk	Necessary soon
> 11	Very High Risk	Immediately

Table 2.5: Evaluation of the final score of the REBA methodology, assigning the risk level and the need to perform changes on the working position [28, p. 205].

In this chapter, the terminology and fundamentals of the methodologies used in the following chapters were described. Procedure III of MIL-HDBK-472 was described in detail, as well as the maintainability allocation by Chipchak. Even if Procedure III is the most suitable one of the five presented military methodologies, it still has numerous drawbacks. For example, the internal access score only considers the relations between the regarded component and the installation space. However, the relations between the components are not taken into account in Procedure III. Also, the body posture or the dimensions of the components are not evaluated in the human factors checklist. Another downside is that the scoring is performed between 0 and 4, which limits the gradation of the considered system properties. This is further amplified by the fact that many questions are only assigned to scores 0, 2 and 4.
Additionally, a brief insight into the methods of Lockett and Luo was given. They served as an inspiration for the self-developed maintainability prediction, which is described in the following chapter. The self-developed procedure aims at compensating the drawbacks of Procedure III, by taking into account more system properties and by using a larger scoring range. Thereby, the body posture is scored based on the REBA procedure, which was also presented in this chapter.

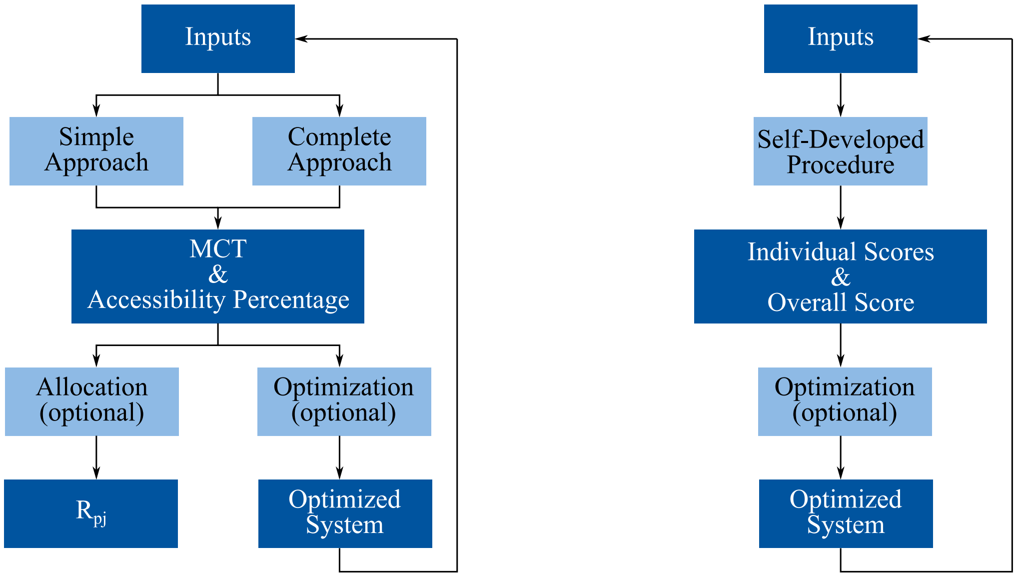
3 Methodology and Implementation

In this chapter the implementation of the methodologies in Mathworks MATLAB, which is used in the framework of this thesis, is described. Both procedures require a system as the main input. If the installation space of the system has more than one maintenance access, it must also be declared for which access the maintainability should be predicted. Additionally, procedure-specific inputs are also required. Those will be further explained in this chapter. After declaring the inputs, the maintainability of the system can be assessed with Procedure III or with the self-developed procedure. The process flow for both procedures is illustrated in figure 3.1.

For Procedure III, there is the choice between a simple and a complete approach. Thereby, the difference is found in the assessment of those questions, that cannot be evaluated automatically with the system information known in the preliminary design stage. The outputs of this procedure are the MCT, but also an accessibility percentage. The last only takes into account the automatically evaluated questions and is used to compare the results of Procedure III to those of the self-developed procedure. The MCT can be compared to the allocated maintenance times R_{pj}, resulting from Chipchak's maintainability allocation.

the self-developed procedure evaluates the maintainability by scoring 14 system and component properties on a detailed scoring range. Thereby, opposing system properties are also included. For instance, the restricted installation space, which is in conflict with an increased space between components. Furthermore, allows the self-developed procedure to use different weighting mechanisms, which will be explained in detail. The self-developed procedure requires additional inputs, like the weighting factors or the working height. The individual scores and an overall score are constitute the output.

An optimization can be performed regarding the output of both procedures. It aims at augmenting the system's maintainability by only changing the component positions. This is performed within predefined boundaries, limiting the allowed movement of the components. The resulting optimized system can then be used as a new input system for both procedures.



(a) Procedure III

(b) Self-Developed Procedure

Figure 3.1: Process flow of the implementation for Procedure III (a) and the self-developed procedure (b).

3.1 Input System

The system is the main input for the maintainability prediction procedures. It is composed of geometrical and functional data of the components and the surrounding installation space. Both, the components and the installation space are defined as cuboids. This information is stored in two variables, '*system*' for the component data and '*space*' for the installation space data. Both variables are created by the use of a graphic user interface (GUI). In this chapter, the general setup of the input system is explained by considering the components, the installation space and the modularization. Afterwards, the specific reference system, used in the further context of this thesis, is described.

3.1.1 Components

The user can add components to the system by using the GUI shown in figure 3.2. It is to be noted, that modularized components are entered individually. They are later combined to modules, as it will be described in sub-chapter 3.1.3.

Several properties must be specified for each component. It begins with the choice of the **component type**, selected from a dropdown menu. Based on the component type, the weighting factor k_{j1} of CHIPCHAK' maintainability allocation is automatically assigned. In addition, a specific color is assigned in the class definition of the component type. This

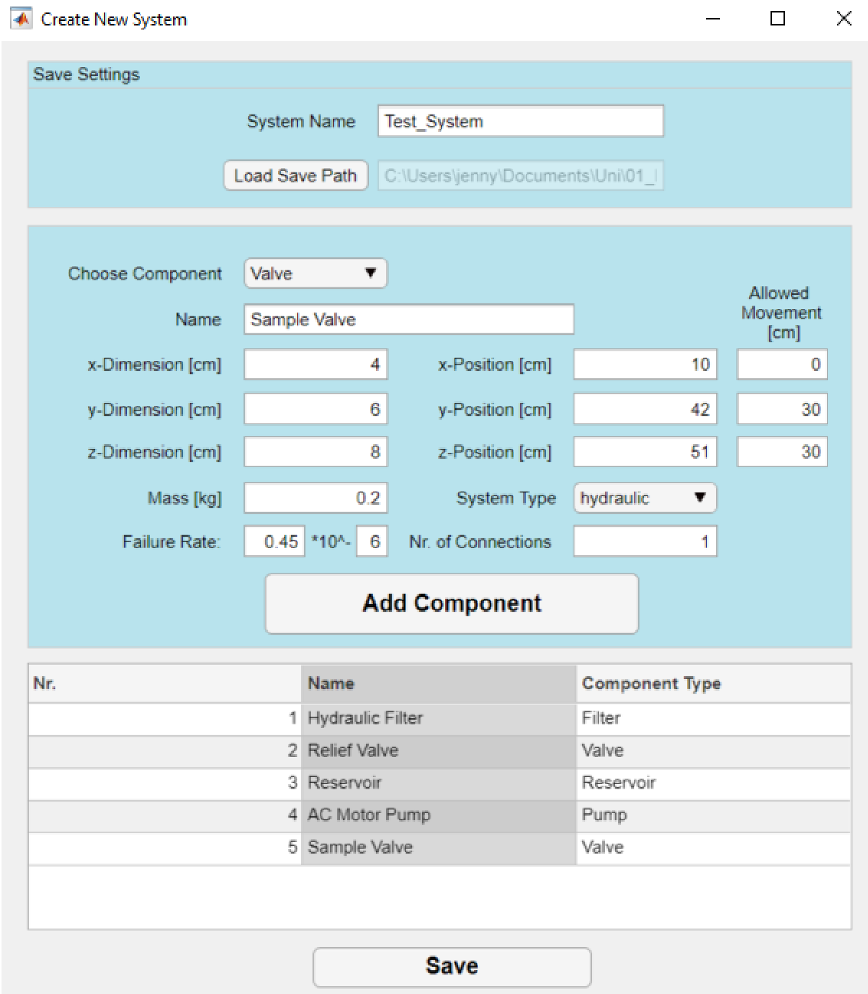


Figure 3.2: GUI used to add components to the system.

facilitates the visible distinction of the different component types in the graphical illustrations of the system.

In the next edit field, the user can enter a **name** for the component. This can be whatever the user wants as it is not used for further functions. However, it is advised to use an unique name for each component, to make the resulting system variable more comprehensible.

In the following, the characteristics of the components are declared. Beginning with the **component's dimension** and **position** in the three axis directions. Those values must be entered as integer *cm* values. This was chosen as a compromise between a high enough level of detail and computation time. For some evaluations, for example the packaging evaluation, the system is transformed into an 3D-array. Thereby, each dimension corresponds to one axis direction and each row or column to 1 *cm*. Additionally, if the system would be defined in *mm* instead of *cm*, the array can exceed the maximum possible array size, due to restricted memory space of the used computer.

On the right of the component position edit fields, there are three more edit fields, labeled with '**Allowed Movement**'. Those are important if the optimization procedure is to be performed with this system. The there entered values define the upper and lower boundaries for the optimizer in each axis direction. Further details will be discussed in chapter 3.5.

The **component mass** must be entered as a kg value and is required for all evaluations which take into account the lifting mass. The **failure rate** is given per flight hour. The exponent is standardly set to 10^{-6}, but it can also be adjusted if the user wishes so.

The **system type** is selected between hydraulic (H), pneumatic (P) and electronic (E). If a component belongs to multiple systems the main system type should be chosen. For instance, a pneumatically pressurized hydraulic reservoir counts towards the hydraulic system. Finally, the last input is the **number of connections** of the component. Both of the last two properties will be used in the self-developed procedure.

The components that have been added to the system are listed in the table underneath the edit fields. The save button saves the variable *system* under the name and folder specified on top of the GUI. This variable is of type *struct* and is shown in figure B.1a. The field 'Component' contains all component properties. This includes all aforementioned information, which was entered by using the GUI. Additionally, the data for the color and k_{j1}, which are defined in the class definition of the component types, are also listed for each component. The structure of the field 'Component' is shown in figure B.1b.

Furthermore, there is an entry called 'connected', which is still empty at this point of the workflow. If the user wants to use the self-developed maintainability prediction, the following step must be performed to fill it. The 'connected' entry contains information about the components connected to the considered one. For this, the user must enter for each component the numbers of the connected components or modules into a provided Excel-Sheet. This will be loaded into a MATLAB code, which automatically adds the 'connected' vector to the respective components.

The components are illustrated as colored cuboids in a 3-dimensional plot shown in figure 3.3. As mentioned before, the color of the component is dependent on its type. This random example contains one reservoir (orange), one filter (pink), one pump (green) and two valves (blue).

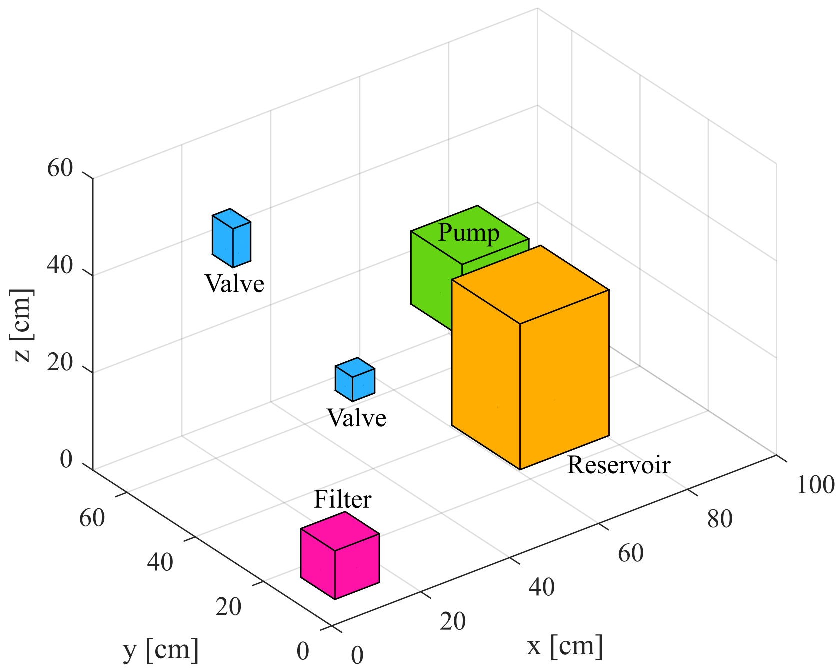


Figure 3.3: Exemplary 3D-illustration of five components.

3.1.2 Installation Space

The components are located within an installation space. It is defined by its dimensions and the maintenance accesses. All the required data can again be entered using a GUI, which is shown in figure 3.4.

The installation space is placed with its lower left front corner in the axis origin. It is sized according to the values entered in the x-, y- and z-dimension edit fields. This coordinate system is used as the reference for the component positions and for all further calculations.

When adding an maintenance access, the user can first choose on which side of the installation space cuboid the opening is placed. Based on this choice, one of the maintenance access dimension and position fields receives a predefined value and is disabled. In the example shown in figure 3.4, the maintenance access is placed in the x-y-plane at z equaling its maximum value. Therefor, the z-dimension equals 0 and the z-position equals 60. After having declared the other two dimensions and positions, the maintenance access is added to the installation space by the ‘Add Opening’ button. The table below contains the properties of the added maintenance accesses.

When all information is entered, the installation space can be saved. The associated variable is called *space* and is shown in figure B.2a for the exemplary installation space. It contains the dimensions and the volume of the installation space as well as the amount of maintenance accesses. The positions and dimensions of the maintenance accesses are stored in the field ‘AccessHoles’, as it can be seen in figure B.2b.

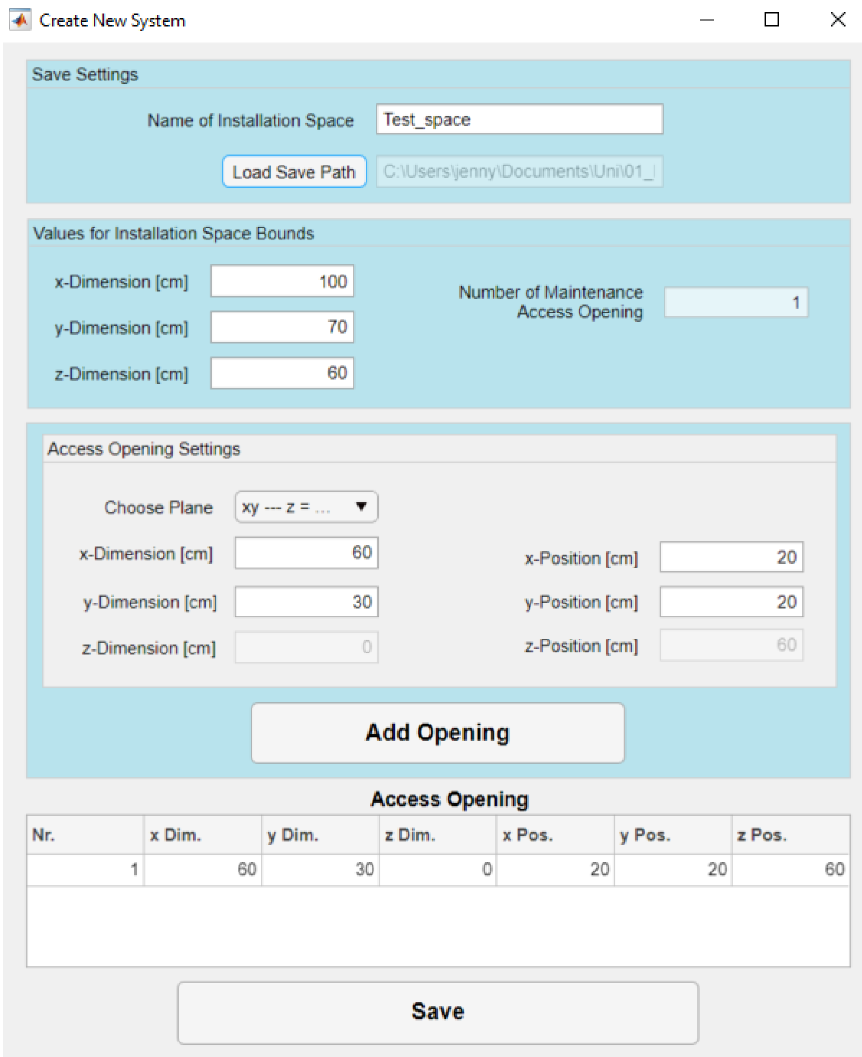


Figure 3.4: GUI used to define the the installation space and its maintenance accesses.

Finally, the installation space is illustrated as a transparent cuboid in light grey. Further, the maintenance accesses are depicted as a rectangle colored in transparent dark grey. For the exemplary system the corresponding illustration is shown in figure 3.5.

3.1.3 Modularization

To reduce the amount of assembly and disassembly steps, multiple components can combined into modules. This is also incorporated in the present implementation. A code is provided to assign components to different modules. The user can enter a 2D-array where each row stands for one module. The column entries are the numbers of the components included in the respective module. Most of the module's properties are defined by its components. The module mass is calculated as the sum of the included component masses. This can optionally be augmented to account for the mass of the module housing. For the factor k_{j1} and the failure rate λ, the safe side was chosen and they are therefor equal to the respective maximum

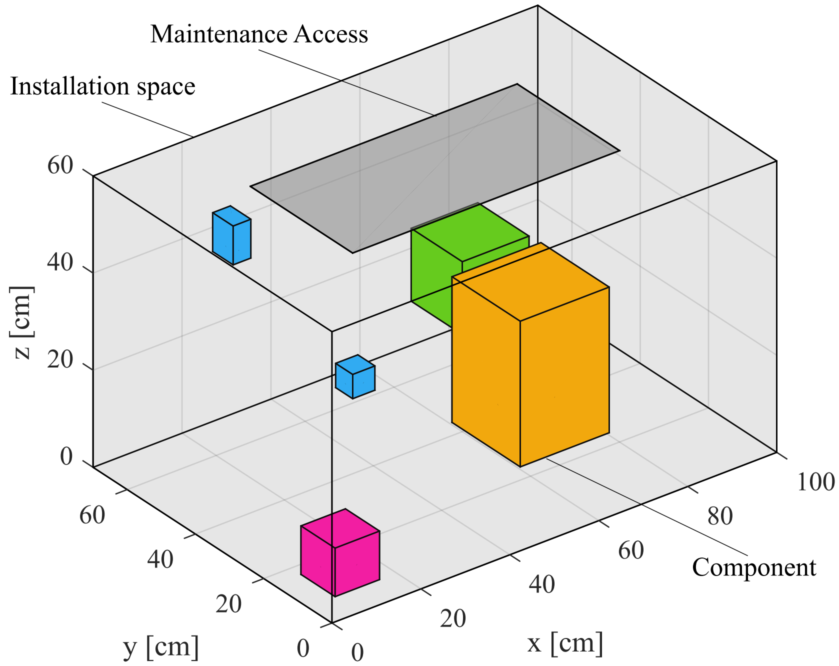


Figure 3.5: Exemplary illustration of the installation space with one maintenance access and five components.

value of the included components. The number of connections of the module must be declared by the user, as this cannot be deduced from the individual components. The 3D-illustration of a system with modules is shown in figure 3.6.

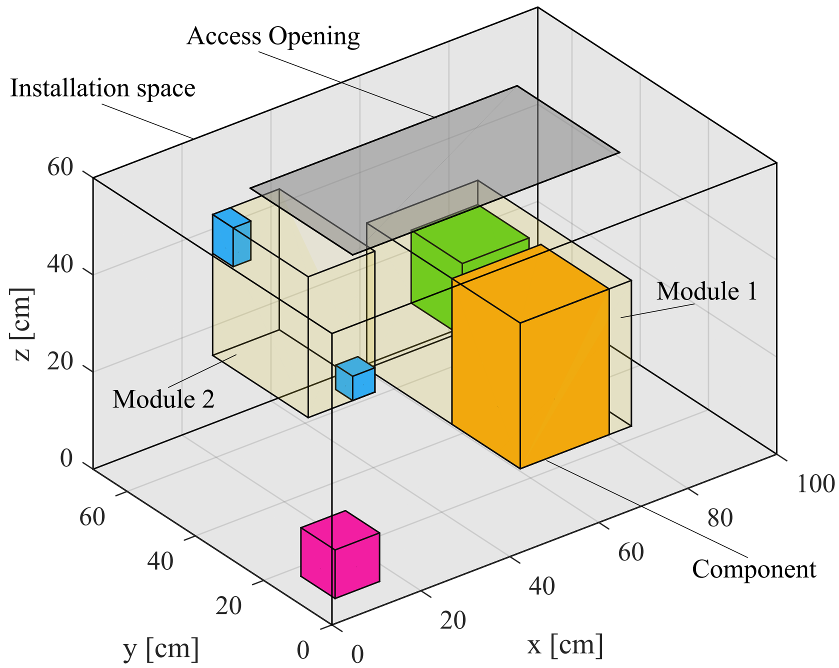


Figure 3.6: Exemplary illustration of the installation space with one maintenance access and five components, whereby four components are combined into modules.

The modules are depicted in transparent yellow, which allows that the individual components are still visible. They are stored in the *system* variable in the same way as normal components. They have an additional property called 'IncludedComp' which is a vector containing the numbers of the components included in the module. The modules are marked with component numbers starting from 10001 for the first module, 10002 for the second and so on. In addition to the already known variable *system*, the variable *system_withoutModules* is also generated and contains the original system before modules were created.

3.1.4 Reference System

The reference system is based on a part of the hydraulic system of a Boeing 777. It was attempted to recreate the system as realistic as possible. However, this could only be achieved to a limited extent due to missing detail information about the original system.

A general overview of the left or right hydraulic system of a Boeing 777 is given in figure 3.7. The system includes a pneumatic part, used to pressurize the hydraulic reservoir. It contains an engine driven pump, an AC motor pump (ACMP) and a filter module for each pump. The hydraulic fluid returning from the actuators is filtered in the return filter module before re-entering the reservoir. It must be mentioned, that this is just a schematic illustration and that the component positions are not realistic.

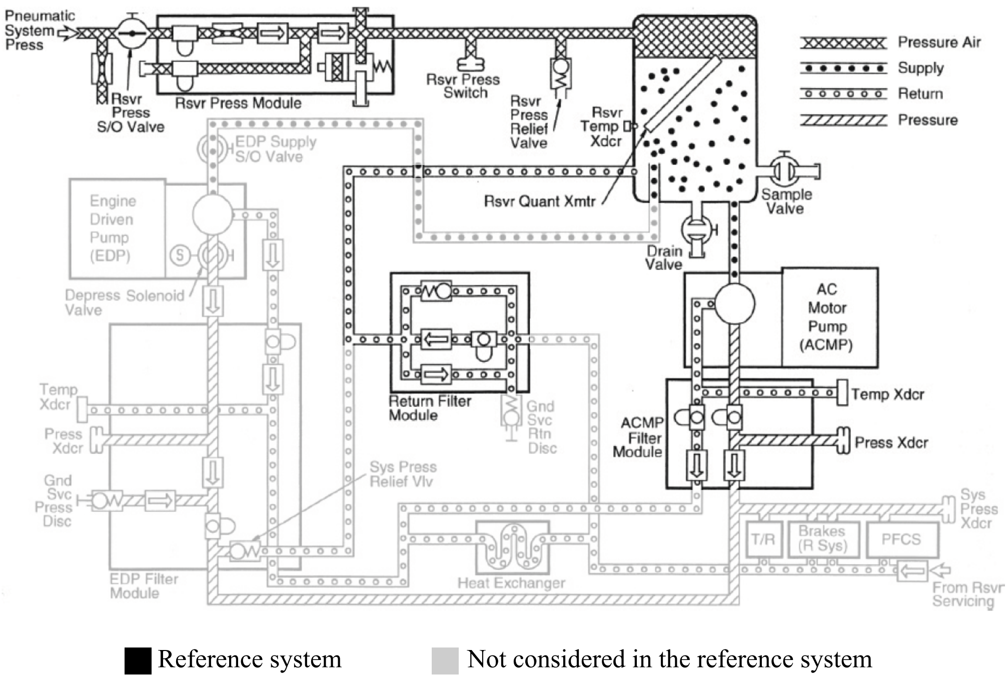


Figure 3.7: Schematic illustration of the left or right main hydraulic system of a Boeing 777 [45, chap. 13.14.].

It was decided, that the compartment placed in vicinity of the center wing box is regarded for the reference system. Based on illustrations in [19, p. 3, 45, chap. 13.14.] it was attempted to detect which components are placed in this hydraulics compartment. The result of those consideration is, that the faded system parts in figure 3.7 are not placed in the regarded compartment and will therefor not be considered in the reference system.

From this follows, that the reference system is composed of the pneumatic pressurization module, shut-off valve, pressure switch, relief valve, hydraulic reservoir, drain valve, sample valve, ACMP and the associated filter module as well as the return filter module. The detailed elements of the three modules must be defined to be able to set the component properties as described in chapter 3.1.1. The pressurization module is illustrated in figure 3.8. It is composed of two filters, two check valves and a manual bleed valve.

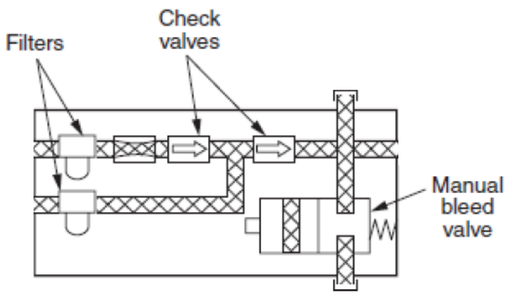


Figure 3.8: Schematic illustration of the pressurization module of the Boeing 777 hydraulic system [45, chap. 13.14.2.].

The components of both filter modules can also be deduced on the basis of figures 3.7 and 3.8. The return filter module contains two valves, one filter and one relief valve. The ACMP filter module consists of two filters and two valves. Table 3.1 contains all individual components with their dimensions and mass. For some components, realistic values were found in product catalogues or similar manufacturer documents. A modified version of this table, containing the associated sources can be found in the appendix in table B.1. Values marked with (*) are however assumptions, that are estimated by taking into account the other values. After having entered the component properties, the three modules are generated. As it can be seen in figure 3.9, the modules are constructed as a solid housing containing the individual components.

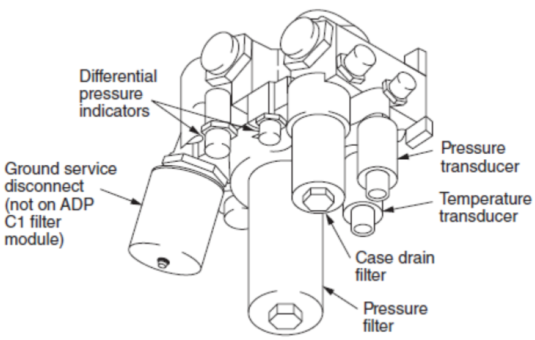


Figure 3.9: Illustration of a filter module of the Boeing 777 hydraulic system [45, chap. 13.14.3.].

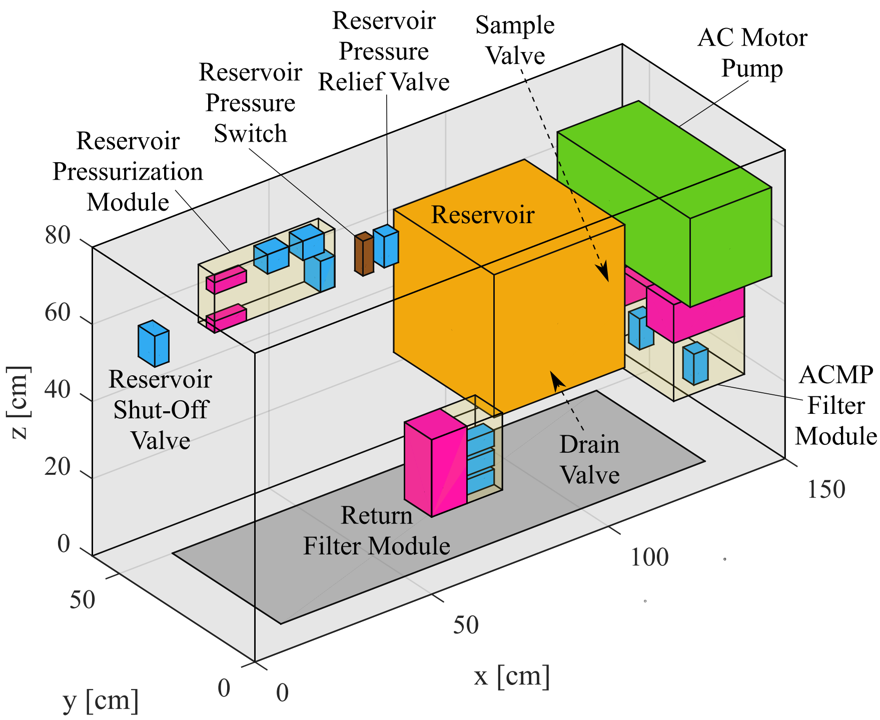
Nr.	Name	Component Type	System	Module	Dimension		Mass		Failure Rate per 10^6 flight hour
1	Reservoir Shut-Off Valve	Valve	P	-	$4\,x\,6\,x\,8\,cm$	(*)	$0.15\,kg$	(*)	31.6611
2	Filter 1 Press. Mod.	Filter	P	Pressurization Module	$3\,x\,3\,x\,9\,cm$		$0.15\,kg$	(*)	0.0499
3	Filter 2 Press. Mod.	Filter	P	Pressurization Module	$3\,x\,3\,x\,9\,cm$		$0.15\,kg$	(*)	0.0499
4	Check Valve 1 Press. Mod.	Valve	P	Pressurization Module	$5\,x\,5\,x\,6\,cm$		$0.48\,kg$		0.4447
5	Check Valve 2 Press. Mod.	Valve	P	Pressurization Module	$5\,x\,5\,x\,6\,cm$		$0.48\,kg$		0.4447
6	Manual Bleed Valve	Valve	P	Pressurization Module	$4\,x\,6\,x\,8\,cm$	(*)	$0.4\,kg$	(*)	1.2063
7	Reservoir Press. Switch	Pressure Switch	P	-	$3\,x\,3\,x\,9\,cm$		$0.113\,kg$		31.6646
8	Reservoir Press. Relief Valve	Valve	P	-	$4\,x\,4\,x\,8\,cm$	(*)	$0.0998\,kg$		7.7949
9	Hydraulic Reservoir	Reservoir	H	-	$37\,x\,37\,x\,37\,cm$		$28.57\,kg$		62.2653
10	Sample Valve	Valve	H	-	$4\,x\,6\,x\,8\,cm$	(*)	$0.15\,kg$	(*)	29.2432
11	Drain Valve	Valve	H	-	$4\,x\,6\,x\,8\,cm$	(*)	$0.15\,kg$	(*)	29.2432
12	AC Motor Pump	Pump	H	-	$23\,x\,23\,x\,49\,cm$		$10\,kg$	(*)	121.4419
13	Relief Valve	Valve	H	Return Filter Module	$4\,x\,4\,x\,8\,cm$	(*)	$0.104\,kg$		0.7292
14	Valve 1 Return Module	Valve	H	Return Filter Module	$4\,x\,4\,x\,8\,cm$	(*)	$0.1\,kg$	(*)	2.2437
15	Valve 2 Return Module	Valve	H	Return Filter Module	$4\,x\,4\,x\,8\,cm$	(*)	$0.1\,kg$	(*)	2.2437
16	Filter Return Module	Filter	H	Return Filter Module	$10\,x\,10\,x\,20\,cm$	(*)	$2\,kg$	(*)	31.5593
17	Filter 1 ACMP Module	Filter	H	ACMP Filter Module	$10\,x\,10\,x\,20\,cm$	(*)	$2\,kg$	(*)	31.5593
18	Filter 2 ACMP Module	Filter	H	ACMP Filter Module	$10\,x\,10\,x\,20\,cm$	(*)	$2\,kg$	(*)	31.5593
19	Valve 1 ACMP Module	Valve	H	ACMP Filter Module	$4\,x\,4\,x\,8\,cm$		$0.1\,kg$		2.2437
20	Valve 2 ACMP Module	Valve	H	ACMP Filter Module	$4\,x\,4\,x\,8\,cm$		$0.1\,kg$		2.2437

Table 3.1: Component list of the reference system.

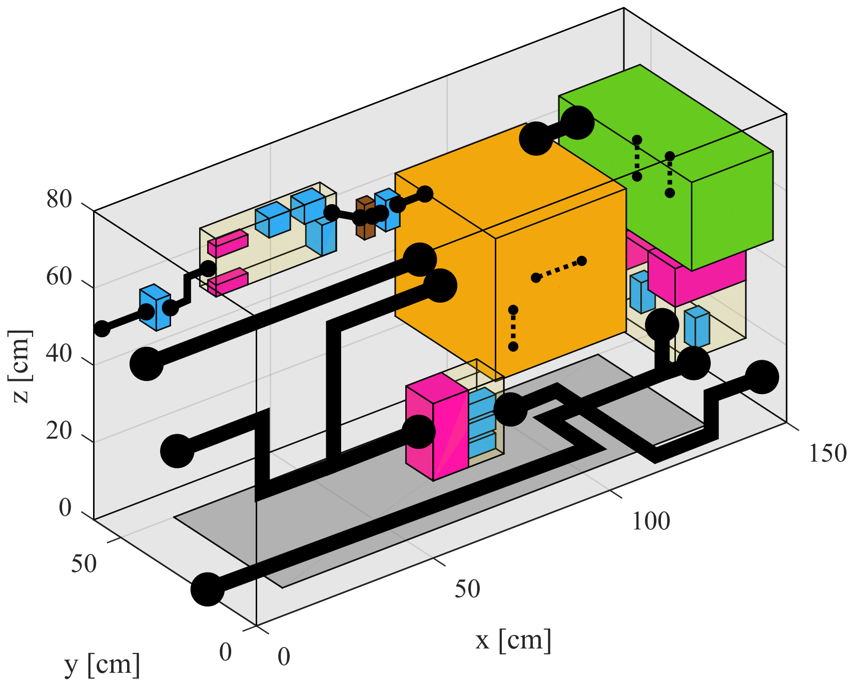
An estimation of the module housing mass had to be made. It was decided to add additional $5\,kg$ to the mass of each module, to account for the solid housing.

Based on the illustrations in figure B.3 and on the component dimensions, the installation space was estimated to have a size of $150\,x\,60\,x\,80\,cm$. The maintenance access is placed in the x-y-plane at $z = 0\,cm$ at $x = 15\,cm$ and $y = 10\,cm$. It is sized $120\,x\,40\,cm$. The reference system is illustrated in figure 3.10a, including all components, modules and the installation space. The drain and sample valve are hidden by the reservoir and are therefor marked with dashed arrows.

In this illustration, only the installation space and the included components are shown, without the lines connecting the components to each other and to other systems. Figure 3.10b was created to give an impression of how the system could look like with connections. It should be noted that these are only assumed connections, based on the schematic representation of the system in figure 3.7. This does not show the real connections within the system and aims only at illustrating that the connections are a significant part of the system.



(a) Reference system with component labels



(b) Reference system with schematic connections

Figure 3.10: 3D-illustration of the implemented reference system.

For the self-developed maintainability prediction, information about the amount of connections of each component must be provided. Likewise, it must be known which components are connected to be able to calculate the distance between them. For the reference system, this information is presented in table 3.2. Again, those are deduced from the schematic system illustration in figure 3.7.

Nr.	Name	Nr. of Connections	Connected Components
10001	Reservoir Pressurization Module	3	1, 7
10002	Return Filter Module	2	9
10003	ACMP Filter Module	6	12
1	Reservoir Shut-Off Valve	2	10001
7	Reservoir Pressure Switch	1	10001, 8
8	Reservoir Pressure Relief Valve	1	7, 9
9	Reservoir	5	10002, 8, 10, 11, 12
10	Sample Valve	1	9
11	Drain Valve	1	9
12	AC Motor Pump	3	10003, 9

Table 3.2: Component list of the reference system with the number of connections and the connected components.

3.2 MIL-HDBK-472 Procedure III

This thesis aims at quantitatively assessing the accessibility of aircraft systems during the preliminary design stage. Therefor, not all information necessary to fully and correctly answer the questions contained in Procedure III is yet known. This concerns, among others, the questions regarding the fastening of components or the need of support from supervising personnel. Another downside is, that the procedure was originally developed to predict the maintenance time of electronic systems, which is why some questions specifically cover electronic aspects. An example is question 6 of checklist A, which evaluates whether the failed parts are of plug-in or solder-in nature. But, as mentioned in chapter 2.2.2, the procedure was validated by Bin Wan Husain for mechanical aviation systems and is therefor also used in this context. Furthermore, the adapted version of checklist C is used.

In detail, the following questions cannot be answered automatically, while only knowing the systems architecture and the component's position, size, mass and failure rate:

Checklist A: Question 1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
Checklist B: Question 1, 2, 4, 5, 7
Checklist C: Question 7

The present implementation provides the option to choose between a simple and complete approach. Using the **complete approach**, the user must answer the aforementioned questions manually and for each component individually. For instance with the help of maintenance task descriptions found in [11] or aircraft specific maintenance planning documents. The user is guided through the questions in a GUI, shown in figure 3.11. Thereby, the automatically answered questions are grayed out and disabled. Beside the answering of the checklist questions, the user must also enter the number of steps needed for the removal of the component, to allow the automatic evaluation of the step-dependent questions of the adapted checklist C.

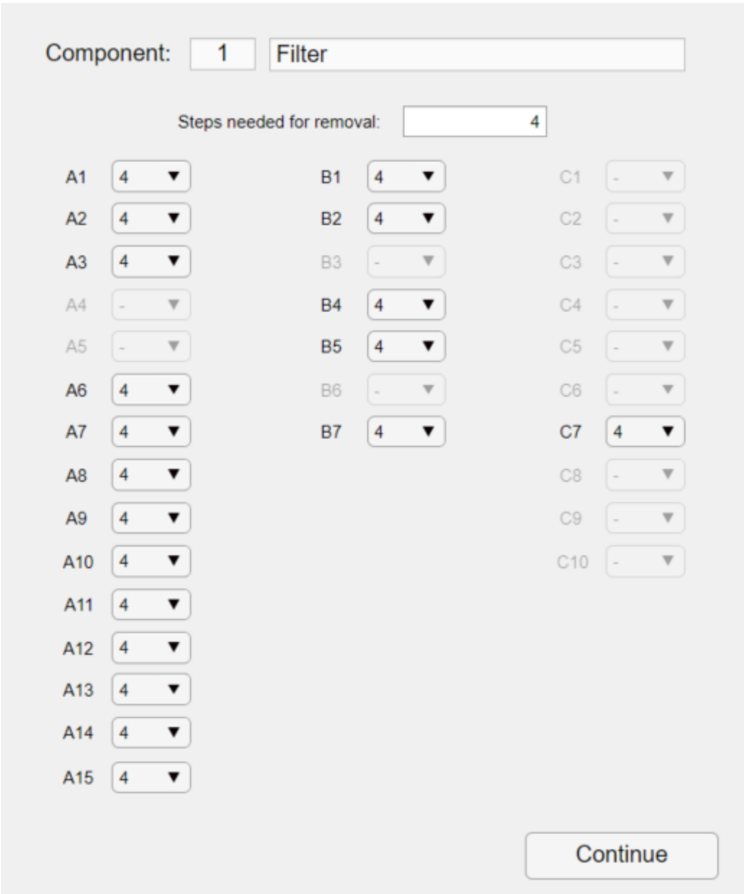


Figure 3.11: GUI used in the complete approach of Procedure III to answer the not automatically evaluated questions.

If the user does not want to or cannot answer all the questions correctly, it is also possible to opt for the **simple approach**. This gives the opportunity to only assess the accessibility and human factor by considering the scores resulting from the systems architecture and component definitions. Of course, with the reduced amount of questions considered, a maintenance task time cannot be calculated. If the user still wishes to get information about the maintenance task time, he can determine the summarized score for the aforementioned not-automatically answered questions of each checklist. The MCT will then be calculated, by the use of equation 2.1, based on the provided scores. The range of those scores is individual for each checklist. Checklist A has 13 questions that cannot be answered automatically. Therefor, the assigned score $C_{A,\,simple}$ for checklist A must be between 0 and $4 \cdot 13 = 52$. Equally, the assigned score $C_{B,\,simple}$ for checklist B is between 0 and 20, and for checklist C the value of

$C_{C,\,simple}$ is between 0 and 4. Within those ranges, the user can freely rate the three criteria design (A), needed facilities (B) and human factor (C) between 'good' and 'bad' in terms of maintainability. Furthermore, for the automatic evaluation of the step-dependent questions of checklist C, the user must also enter a number for the steps of removal. In contrast to the complete approach, the removal steps are not entered for each component individually. To further simplify the inputs, just one number of removal steps is chosen, which is used for every component of the system.

Both, the simple and the complete approach, include the same automatic evaluations of the remaining questions, with the detailed considerations being explained in the following.

Question A4 covers the internal access to the component. This means, that it should be checked if visual and/or manipulative access to the component is possible. In simpler terms, it is assessed whether a component can be seen and/or grabbed after all additional work needed to gain access to the component was performed. This involves the removal of blocking components or covers of the external maintenance access [16, p. A3-36]. In this implementation, the internal access is evaluated based on the position of the component in relation to the maintenance access. As it can be seen in figure 3.12, there are three cases. Based on them, a first evaluation of the internal access is performed. The visual access is given if the component is fully or partially visible, when looking at an angle of 90° through the maintenance access. This is fulfilled in case 1 and 2. The manipulative access, also called haptic access, is given in case 1, but it must be further evaluated in case 2 and 3.

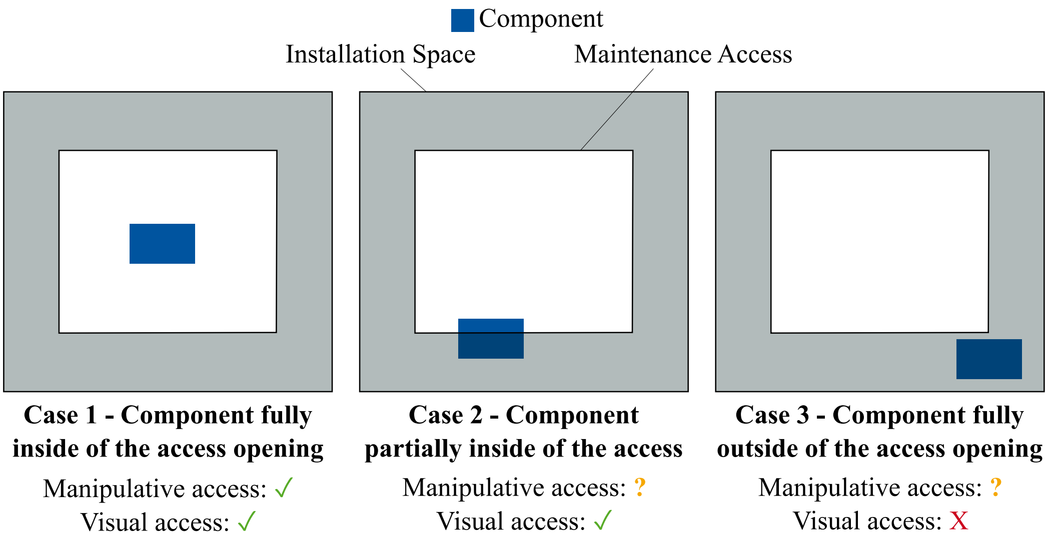


Figure 3.12: Three cases based on the positioning of the component in relation to the maintenance access and the associated evaluation of the manipulative and visual access.

It is checked, if the space between the component and the boundaries of the installation space is big enough to fit a flat hand. The required space for a flat hand was defined by RIGBY [41, p. 45] as 2.25". This value was converted to SI-units and rounded up from

5.715 cm to 6 cm. If this criteria is fulfilled, the manipulative access is given and vice versa it is not given if the space is smaller than required. Finally, question A4 is scored according to table 3.3.

Question	Scored Design Factor	Consideration	Score
4	Access (Internal)	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

Table 3.3: Scores and considerations for question 4 of checklist A of Procedure III [16, p. 3-36].

The evaluation only takes into account if the haptic or visual access to the component is possible. It does not consider to which extent the access is possible. Therefor, components that are partially visible are treated equally, in terms of visual access, as components that are fully visible. Also, the relations between the components are not considered for the manipulative access.

Question A5 takes into account the amount of disassembly required to gain access to the considered component, also called 'packaging'. As it can be seen in table A.1, the disassembly is originally scored by using time values. As this implementation targets the preliminary design stage, the exact mounting of the components is not yet known. As a result, it cannot be calculated how much time the removal of a certain component requires. Therefor, it was decided to score question A5 by the amount of components that need to be removed. If no removal is needed, the score will be 4. If one component needs to be removed, the score will be 2. In all other cases the score will be 0. Same as in table A.1, the scores 1 and 3 are not used for this question. The search area which is scanned for the existence of other components, is shown in figure 3.13.

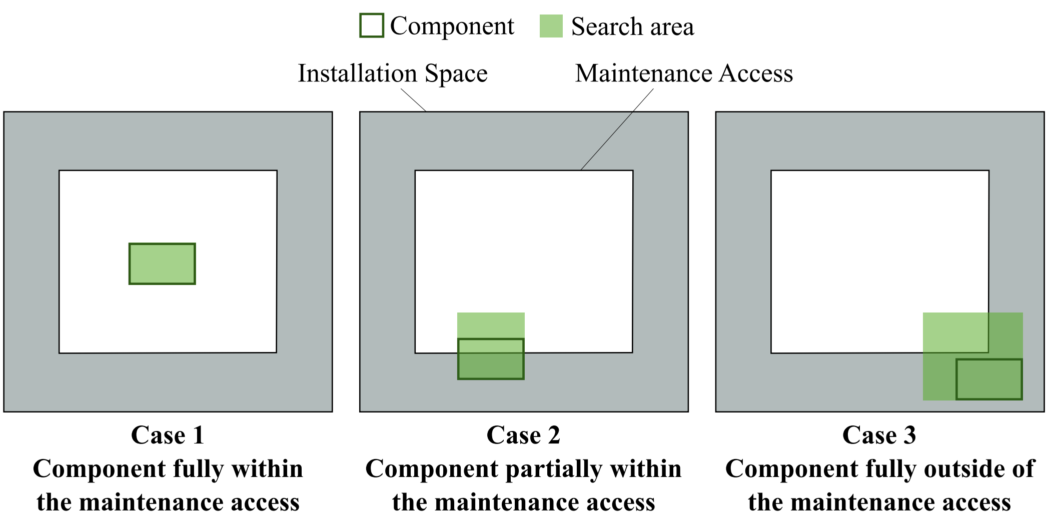


Figure 3.13: Area that is scanned for the existence of other components.

To detect the components which have to be removed, it is first checked if any other component is placed ‘on top’ of the regarded component. ‘On top’ means in this context, between the component and the plane in which the maintenance access is placed. For the aforementioned cases 2 or 3, it must also be checked if the lateral displacement towards the maintenance access is not blocked by other components.
If the component does not fit through the maintenance access without being turned or tilted, it is assumed, that, in order to have enough space for this, all other components must be removed. Therefor, the score for question A5 will be equal to 0 in this special case.

In the facilities checklist, the questions B3 and B6 are both answered based on the mass of the component, as shown in table 3.4. The lifting mass limits are defined for male and female persons in the literature. Therefor, the following evaluation is defined for male, female and mixed maintenance crews.

Score	Female Crew	
	B3	**B6**
4	$m \leq 20\,kg$	$m \leq 10\,kg$
2	-	$10\,kg < m \leq 20\,kg$
0	$20\,kg < m$	$20\,kg < m$
	Male Crew	
	B3	**B6**
4	$m \leq 60\,kg$	$m \leq 30\,kg$
2	-	$30\,kg < m \leq 60\,kg$
0	$60\,kg < m$	$60\,kg < m$
	Mixed Crew	
	B3	**B6**
4	$m \leq 40\,kg$	$m \leq 30\,kg$
2	-	$30\,kg < m \leq 40\,kg$
0	$40\,kg < m$	$40\,kg < m$

Table 3.4: Scoring of questions B3 and B6 based on the maximum lifting load [18, p. 41].

Question B3 takes into account the need of additional material to perform the maintenance task. If the component mass is smaller than the mass that can be lifted by two persons, it is assumed that the task can be performed without additional equipment, thus the score for B3 will be 4. If the component mass is larger than the mass that can be lifted by two persons, an external lifting device, including lifting straps or other additional equipment, will be required and the score for B3 is equal to 0. For frequent lifting, the maximum component mass appropriate to be lifted by a male person is $30\,kg$ and for a female person it is equal to $10\,kg$ [18, p. 41]. For all-male or all-female maintenance crews those values are doubled to obtain the lifting limit for two persons. For a mixed crew, the appropriate lifting masses for one male and one female person are added, resulting in a value of $40\,kg$.

Question B6 considers whether the performance of the maintenance task requires more than one mechanic. If the component is heavier than the above mentioned maximum lifting mass for one person, a second person will be required and the score for question B6 will therefor

be equal to 2. In the other case, the score equals 4. If the component mass even exceeds the lifting mass for two persons, the score will be 0. For a mixed maintenance crew 40 kg are used as the limit for being lifted by two persons. The limit for one person equals the limit for a male person in this case.
Both questions, B3 and B6, only take into account if additional personal is required and they do not consider if the maintenance access is large enough to allow two persons to work inside of it.

In checklist C, all but one question can be answered automatically by using the adaptation from Bin Wan Husain [6, p. 78 ff.]. While questions C1 and C2 are dependent on the component mass, questions C3 to C6 and C8 to C10 can be scored by the amount of steps needed for the removal of the component.

For **question C1** (Arm, leg & back strength) it was decided to use a procedure from directive BGI 582 '*Safety and Health Protection during Transport and Storage Work*' [5, p. 15 ff.]. The effort concerning arm, leg and back strength is evaluated using factors for load, posture, time and execution. While the first one is calculated based on the component mass, the remaining three must be declared in advance. For those factors, the following assumption is made regarding the lifting during maintenance tasks. It is assumed, that lifting tasks are performed between 10 and 40 time per work shift, in a slightly restricted moving space and with wide forward bending or load far from body or above shoulder height. This results in time factor $F_T = 2$, posture factor $F_P = 4$ and execution factor $F_E = 1$. The load factor F_L is assigned based on the component mass and the gender of the mechanic according to table 3.5. For mixed crews, the values for a male person are considered.

Load for male person	Load for female person	Load factor
$m < 10\,kg$	$m < 5\,kg$	1
$10\,kg \leq m < 20\,kg$	$5\,kg \leq m < 10\,kg$	2
$20\,kg \leq m < 30\,kg$	$10\,kg \leq m < 15\,kg$	4
$30\,kg \leq m < 40\,kg$	$15\,kg \leq m < 25\,kg$	7
$40\,kg \leq m$	$25\,kg \leq m$	25

Table 3.5: Load factor assignment according to BGI 582 [5, p. 17].

The total points are calculated by equation 3.1. A scoring for question C1 was implemented based on the resulting value F_{total} and it is shown in table 3.6.

$$F_{total} = (F_L + F_P + F_E) \cdot F_T \tag{3.1}$$

Points	$F_{total} < 10$	$10 \leq F_{total} < 22$	$22 \leq F_{total} < 35$	$35 \leq F_{total} < 50$	$50 \leq F_{total}$
Score C1	4	3	2	1	0

Table 3.6: Allocation of score C1 according to F_{total}, based on BGI 582 [5, p. 19].

Question C2 takes into account endurance and energy. The detailed scoring, based on the component mass, can be seen in table 3.7. For a female mechanic, the allocated component mass limits will be divided by two, referring to [18, p. 41].

Component mass	$m < 8\,kg$	$8\,kg \leq m < 15\,kg$	$15\,kg \leq m < 23\,kg$	$23\,kg \leq m < 40\,kg$	$40\,kg \leq m$
Score C2	4	3	2	1	0

Table 3.7: Allocation of score C2 based on the component mass [6, p. 80].

The remaining questions of checklist C, with the exception of question 7, are scored according to the total amount of steps $s_{total,\,i}$ needed to remove the component. As explained before, the number of steps is assigned differently for the simple and the complete approach. The total step count $s_{total,\,i}$ for component i is calculated using equation 3.2. The individual step count s_i of the regarded component is added to the steps needed to remove the blocking components m. Those are detected in question A5. The resulting total step count $s_{total,\,i}$ is transformed to the score for questions C3, C4, C5, C6, C8, C9 and C10 according to table 3.8. The corresponding score is referred to as C_{steps} in the following. All of those scores have the same value for one component.

$$s_{total,\,i} = s_i + \sum_{j=1}^{m} s_j \tag{3.2}$$

Steps	$s_{total,\,i} < 4$	$4 \leq s_{total,\,i} < 7$	$7 \leq s_{total,\,i} < 10$	$10 \leq s_{total,\,i} < 13$	$13 \leq s_{total,\,i}$
Score C_{steps}	4	3	2	1	0

Table 3.8: Allocation of the score for questions C3, C4, C5, C6, C8, C9 and C10 according to the total amount of steps $s_{total,\,i}$ needed to remove the component. Scoring according to Bin Wan Husain [6, p. 82].

Procedure III requires different inputs, depending on if the simple or the complete approach is chosen. The following list gives an overview on the required inputs for both approaches.

Simple Approach $C_{A,\,simple}$, $C_{B,\,simple}$, $C_{C,\,simple}$ and one value for the removal steps

Complete Approach Individual scores for all not-automatically evaluated questions for each component and the removal steps for each component. The last two inputs are entered by using the GUI in figure 3.11.

In addition to those, both approaches also require an input system, the number of the considered maintenance access and the gender of the maintenance crew as common inputs.

3.3 Maintainability Allocation

In the here presented automatic evaluation of an aircraft system's maintainability, the allocated active repair time R_{pj} can also be considered, according to the methodology presented in chapter 2.3. Of the three weighting factors, only k_{j3} is evaluated based on the system properties. The factor k_{j1} depends on the component type and is pre-allocated in the class definition of each component type. The factor must therefor only be defined when adding a new component type to the implementation and not when creating a system. It is assigned based on the adapted module list from Bin Wan Husain, which can be found on the right side of table 2.2.

As it can be seen in table 2.3, the factor k_{j2} takes into account the fault isolation technique of the system. The fault isolation can be manual, semiautomatic or automatic. The assignment of factor k_{j2} must be made by the user.

To determine the value of k_{j3}, the handling and access characteristics are considered separately. The scoring happens to be the exact opposite of the scoring in Procedure III. This means, that a score of 4 corresponds to the worst score and the score 0 is the best possible score. As it can be seen in equation 3.3, the score for the access characteristic is simply calculated by reducing 4 by the score of question A5 (Packaging) of Procedure III.

$$k_{j3_{access}} = 4 - C_{A5} \tag{3.3}$$

The handling is evaluated based on the scores of questions B3 (Jigs or Fixtures) and B6 (Technical Assistance). The used calculations are shown in equation 3.4. If the score B3 equals 0, the component mass is too large to be lifted by two persons and therefor additional equipment, like a hoist lift, is required. This is the worst possible case in terms of handling and results in $k_{j3_{handling}} = 4$. If no additional equipment is needed, $k_{j3_{handling}}$ is calculated based on the score B6. This question considers whether one or two mechanics are required to perform the task. The calculation shown in equation 3.4, transforms the scoring of Procedure III to the scoring used in the maintainability allocation.
The final value for k_{j3} is calculated according to equation 3.5, by taking the maximum of $k_{j3_{access}}$ and $k_{j3_{handling}}$.

$$\begin{aligned} &\text{If } C_{B3} = 0: \\ &\quad k_{j3_{handling}} = 4 \\ &\text{If } C_{B3} \neq 0: \\ &\quad k_{j3_{handling}} = 4 - C_{B6} \end{aligned} \tag{3.4}$$

$$k_{j3} = max(k_{j3_{access}}; k_{j3_{handling}}) \tag{3.5}$$

As explained in chapter 2.3, the MTTR can be defined in different ways. One possibility is to calculate the MTTR based on the MCT values predicted by the use of Procedure III.

This procedure was suggested by BIN WAN HUSAIN [6, chap. 7]. In this case, the MTTR is calculated by equation 3.6 as the average of the MCT values for all components.

$$MTTR = \frac{\sum_{i=1}^{n} MCT_n}{n} \tag{3.6}$$

While this is implemented as the standard in this tool the user can also opt for one of the other two possibilities that are presented in chapter 2.3. The other options are to predefine the MTTR or to calculate it based on the inherent availability and the MTBF. In those cases, the MTTR or A_i must be provided as inputs by the user. The MTBF is calculated based on the failure rates λ of the components. The allocated maintenance times R_{pj} is finally calculated using equation 2.4.

3.4 Self-Developed Maintainability Prediction

The self-developed procedure was inspired by the methodologies of LOCKETT and LUO, both presented in chapter 2.2.3. The methodology of LOCKETT [31] scores different system properties that influence the maintainability, between 0 and 2. The overall maintainability is evaluated based on the achieved total score compared to the maximum possible overall score. The basics of this methodology are taken as the foundation of the here presented self-developed procedure. Thereby, a different scoring range was chosen to have more gradation between the highest and lowest scores. The methodology of LUO [33] is focused on the trade-off between a minimal occupied volume and enough space between the components to perform the maintenance tasks. The basic concept of this methodology is also incorporated in the self-developed procedure.

The here presented procedure aims at overcoming the already mentioned drawbacks of Procedure III. For example, Procedure III does not consider the relations between the components, the occupied volume, the component size or the body posture. Several scoring questions are also not suited for an objective and automatic evaluation during the preliminary design phase. Additionally, the scoring between 0 and 4, as used in Procedure III, does not allow a detailed evaluation of the system properties.

The self-developed procedure includes only system properties that allow an objective scoring. Some properties that are missing in Procedure III are also incorporated in the here presented procedure. The maintainability is evaluated by taking into account the influences of the system's geometry, accessibility and the human factor. A checklist was created for each of those three influences, considering different system properties. A scoring factor S is introduced for each property, based on those, the scoring is performed according to tables 3.9, 3.10 and 3.13. The scores C have values between 1 and 10, where 1 represents the worst and 10 the best possible scenario in terms of maintainability. This scoring range allows a more precise evaluation of the maintainability. The detailed calculations and considerations are explained in the following.

Some properties are not defined by the overall system, but by the characteristics of the individual components. The concerned scoring factors are marked with index i and are scored for each component individually. In the following, those scores are referred to as 'component-dependent scores'.

The scores $C_{p,\,i}$ for each checklist are determined component-wise and are summarized to the overall value C_p according to equation 3.7 using an optional weighting factor W_i. The index p is to be replaced with the checklist name. The term W_i is a weighting factor based on the failure rate λ of the component i and is calculated as shown in equation 3.8. This is an optional feature to give components with a higher failure rate more impact on the overall score. If the feature is not used, the weighting factor W_i equals one for each component.

$$C_p = \frac{\sum_{i=1}^{n} C_{p,\,i} \cdot W_i}{\sum_{i=1}^{n} W_i} \tag{3.7}$$

$$W_i = max(1\,;\, round(\lambda \cdot 10^5)) \tag{3.8}$$

The final score C_{total} is calculated by equation 3.9 based on the checklist scores C_{geo}, C_{acc} and C_{HF}. Those are, as explained, calculated using equation 3.7. The scores are each multiplied by the associated weighting factors W_{geo}, W_{acc} and W_{HF}, which can be manually set by the user. If each checklist should have the same impact on the final score, the weighting factors are set to 1.

$$C_{total} = \frac{W_{geo} \cdot C_{geo} + W_{acc} \cdot C_{acc} + W_{HF} \cdot C_{HF}}{W_{geo} + W_{acc} + W_{HF}} \tag{3.9}$$

Equally, the total score can also be calculated for each component individually by the following equation 3.10.

$$C_{total,\,i} = \frac{W_{geo} \cdot C_{geo,\,i} + W_{acc} \cdot C_{acc,\,i} + W_{HF} \cdot C_{HF,\,i}}{W_{geo} + W_{acc} + W_{HF}} \tag{3.10}$$

As for Procedure III, the main input of the self-developed procedure is the input system and the number of the regarded maintenance access. Furthermore, the weighting factors W_{geo}, W_{acc} and W_{HF} must be declared by the user. Also, it must be chosen if the component-dependent weighting mechanism is to be used. The last input is the working height h_w, which describes the z-wise distance between the floor of the working area and the bottom side of the installation space. Since the coordinate system is placed in the lower left front corner of the installation space, the working height also equals the distance between the floor and the coordinate system. The working height is required for the evaluation of the body posture.

3.4.1 Geometry Checklist

The so called *geometry checklist* scores the geometrical properties of the system considering if the components fit through the maintenance access, the total volume occupied by the components and the distance between connected components. In detail, the individual considerations and associated scoring factors are as follows.

Fit through access The component dimensions are compared to the dimensions of the maintenance access. If the component does not fit through the maintenance access in the same direction as it is installed, it is further checked if the component fits through it after being turned or tilted. If the component does not fit through the maintenance access at all, it must be disassembled into smaller units within the installation space, resulting in a larger maintenance effort. According to this evaluation, the scoring factor is assigned as shown in equation 3.11.

$$S_{fit,i} = \begin{cases} 2, & \text{if the component fits without turning/tilting} \\ 1, & \text{if the component fits with turning/tilting} \\ 0, & \text{if the component does not fit through the access} \end{cases} \tag{3.11}$$

Occupied volume The occupied volume stretches between the minimum and maximum component-coordinates in each axis direction. This is illustrated in figure 3.14 for an exemplary system containing five different components.

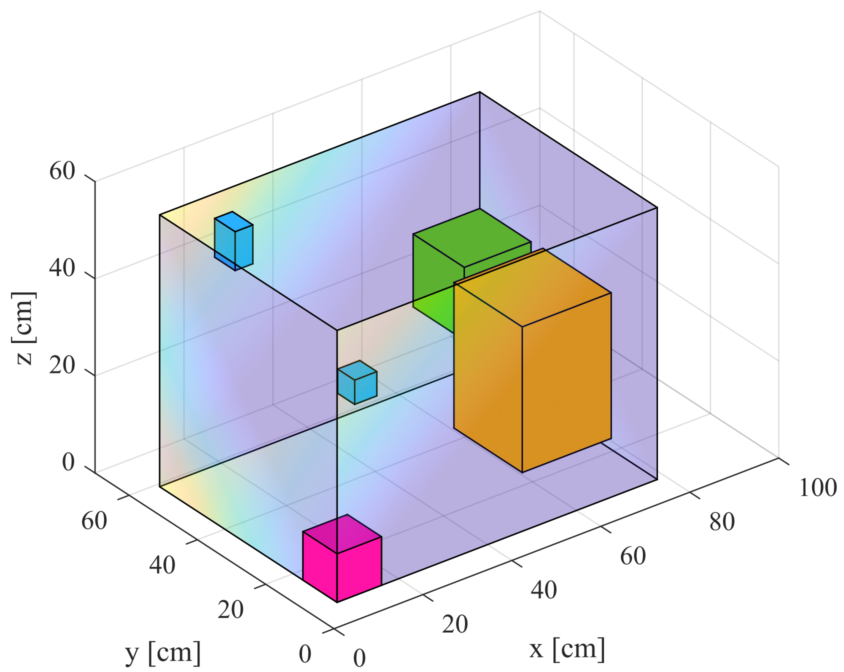


Figure 3.14: Occupied volume (transparent colored cuboid) spanned by five different components (solid cuboids).

For the scoring factor S_{vol}, the percentage of the occupied volume in relation to the maximum possible volume is calculated using equation 3.12. The maximum volume V_{max} corresponds to the total volume of the installation space. The efficient use of the available space and the trade-off regarding the available space between the components was also considered by Luo et al. [33, p. 1836].

$$S_{vol} = \frac{V_{occupied}}{V_{max}} \cdot 100 \tag{3.12}$$

Distance between connected components The distance between connected components determines the amount of hydraulic, pneumatic or electronic lines in the system. To avoid additional mass and additional occupied volume caused by longer lines, a smaller distance between connected components is preferable. For each component i, the length $l_{i,j}$ of the connection to every connected component j is calculated as the sum of the distance δ in x-, y- and z-direction between the center of both components. The calculation is shown in equation 3.13. The lengths $l_{i,j}$ are summarized, as it can be seen in equation 3.14, resulting in a total connection length $l_{total,i}$ for each component i.

$$l_{i,j} = \delta_x + \delta_y + \delta_z, \text{ for } i = 1...n \text{ and } j = 1...N_i \tag{3.13}$$

$$l_{total,i} = \sum_{j=1}^{N_i} l_{i,j} \tag{3.14}$$

The final calculation of the scoring factor $S_{ConLength,i}$ is performed according to equation 3.15, using the maximum possible connection length l_{max}, the amount of connected components N_i and a reducing factor b. The maximum connection length l_{max} is defined as the sum of the three dimensions of the installation space. The reducing factor b is used to account for the distinctions between the different system types. For hydraulic and pneumatic systems, the reducing factor is set to 1 and is therefor negligible. For electronic systems, b equals 1.5.

$$S_{ConLength,i} = \frac{l_{total,i}}{b \cdot N_i \cdot l_{max}} \cdot 100\% \tag{3.15}$$

The values for b are based on comparisons of the mass per meter and the pressure loss per meter for the different system types. The complete calculations can be found in appendix B. From the results follows, that pneumatic and electronic systems have a similar mass per meter line. The pressure loss in hydraulic systems was estimated to $6.15 \cdot 10^{-7}\%$ of the system pressure per meter and is therefor negligible. On the other side, the pressure loss in pneumatic systems is more significant with 0.57% of the system pressure per meter line. Electronic systems have of course no pressure loss, but they feature a growing resistance with growing cable length. An overview of the results is also given in table B.2. It was decided, that based on those observations no system type has a significant advantage or disadvantage over the other system types. However, electronic systems have still been given a slight advantage by using the reducing factor $b = 1.5$. This is founded on the fact that electronic lines are more flexible and likely have smaller diameters and therefor consume less space. In addition to this, the use of other conductor materials than copper, can also result in a lower mass per meter and therefor in another advantage for electronic systems.

For each of the three geometrical influences, the corresponding score is assigned, based on the scoring factors S, according to table 3.9.

Score	Fit through access	Occupied Volume	Distance between conencted components
1	$S_{fit,\,i} = 0$	$90\,\% \leq S_{vol}$	$90\,\% \leq S_{ConLength,\,i}$
2	-	$80\,\% \leq S_{vol} < 90\,\%$	$80\,\% \leq S_{ConLength,\,i} < 90\,\%$
3	-	$70\,\% \leq S_{vol} < 80\,\%$	$70\,\% \leq S_{ConLength,\,i} < 80\,\%$
4	-	$60\,\% \leq S_{vol} < 70\,\%$	$60\,\% \leq S_{ConLength,\,i} < 70\,\%$
5	-	$50\,\% \leq S_{vol} < 60\,\%$	$50\,\% \leq S_{ConLength,\,i} < 60\,\%$
6	-	$40\,\% \leq S_{vol} < 50\,\%$	$40\,\% \leq S_{ConLength,\,i} < 50\,\%$
7	-	$30\,\% \leq S_{vol} < 40\,\%$	$30\,\% \leq S_{ConLength,\,i} < 40\,\%$
8	$S_{fit,\,i} = 1$	$20\,\% \leq S_{vol} < 30\,\%$	$20\,\% \leq S_{ConLength,\,i} < 30\,\%$
9	-	$10\,\% \leq S_{vol} < 20\,\%$	$10\,\% \leq S_{ConLength,\,i} < 20\,\%$
10	$S_{fit,\,i} = 2$	$0\,\% \leq S_{vol} < 10\,\%$	$0\,\% \leq S_{ConLength,\,i} < 10\,\%$

Table 3.9: Geometry checklist of the self-developed procedure.

The component-dependent scores for the geometry checklist are calculated by taking the mean of the scores for fit through access, occupied volume and the distance between connected components, as seen in the following equation 3.16.

$$C_{geo,\,i} = \frac{C_{fit,\,i} + C_{vol} + C_{ConLength,\,i}}{3} \tag{3.16}$$

The overall score for the geometry checklist is called C_{geo} and it is calculated by using equation 3.17, which corresponds to the application of equation 3.7 to the geometry checklist. The geometry score of each component is multiplied by its weighting factor W_i. The sum of those values is divided by the sum of the weighting factors W_i.

$$C_{geo} = \frac{\sum\limits_{i=1}^{n} C_{geo,\,i} \cdot W_i}{\sum\limits_{i=1}^{n} W_i} \tag{3.17}$$

3.4.2 Accessibility Checklist

The *accessibility checklist* takes into account the ease of accessing the components within the installation space. This includes, similar as explained in chapter 2.2.2, the haptic and visual access to the component itself and the packaging of the system. Additionally, the available space around the component and the amount of connections are evaluated.

Haptic access The haptic access is verified for each component individually. For this, the space between the regarded component and the boundaries of the installation space is evaluated, not taking into account other components. It was decided, that haptic access is granted if there is enough space to fit a flat hand in between. The needed reference value originates from the required space of 2.25” for a flat hand by Rigby [41, p.45]. Transformed to SI-Units and rounded, this results in a distance of 6 cm required between the component and installation space boundaries for haptic access. As it can be seen in the accessibility checklist in table 3.10, the score C_{hapt} depends on the number of accessible component sides and the corresponding axis directions. The optimal score of 10 corresponds to a component accessible from 5 or more sides. This takes into account that one component side is often not haptically accessible because of the fixture of the component.

Visual access The evaluation of the visual access considers if the component is visible while looking straight through the maintenance access and while disregarding other components. The scoring factor $S_{vis,\,i}$ is defined as the percentage of the visible upper surface area $A_{visible}$ of the component compared to the total upper surface area A_{total} of the component. An example for the case, that the maintenance access is located in the x-y-plane, is shown in equation 3.18. Thereby, dim stands for the component dimension in the respective axis direction. If S_{vis} equals to 100 %, the component is fully visible. Vice versa, S_{vis} equaling to 0 % corresponds to a component fully hidden by the installation space housing.

$$S_{vis,\,i} = \frac{A_{visible}}{A_{total}} \cdot 100\% = \frac{dim_{x,\,visible} \cdot dim_{y,\,visible}}{dim_x \cdot dim_y} \cdot 100\% \tag{3.18}$$

Packaging The packaging evaluation considers the amount of components that have to be removed before being able to remove the regarded component. This number also corresponds to the scoring factor $S_{pack,\,i}$. The procedure is identical with the procedure used in the implementation of Procedure III, described in chapter 3.2. An exemption is made for components that do not fit through the maintenance access or that have to be turned to fit through it. For those components, it is assumed, that all other components must be removed to have enough space to turn or disassemble the component.

Available space around the component The aforementioned evaluation of the haptic access only takes into account which sides of the component are reachable, while only regarding the distance to the installation space boundaries. In contrast to this, the available space around the component is evaluated in the coordinate plane where the maintenance access is placed, taking into account the installation space and the other components. The procedure is schematically illustrated in figure 3.15.

To check the available space, cubic volumes around the component are examined for the existence of other components or installation space boundaries. The first cuboid is on each side 1 cm larger than the component. If there are no hindering objects in the examined volume, the dimensions are increased by another 1 cm on each side. This is repeated until other components or installation space boundaries are reached. The scoring factor $S_{space,\,i}$ equals the available space d_{avlb}. The scoring is performed using reference sizes for a flat hand (6 cm), a fist (9 cm), a hand plus small round object (10 cm) and an arm (13 cm) [41, p. 45].

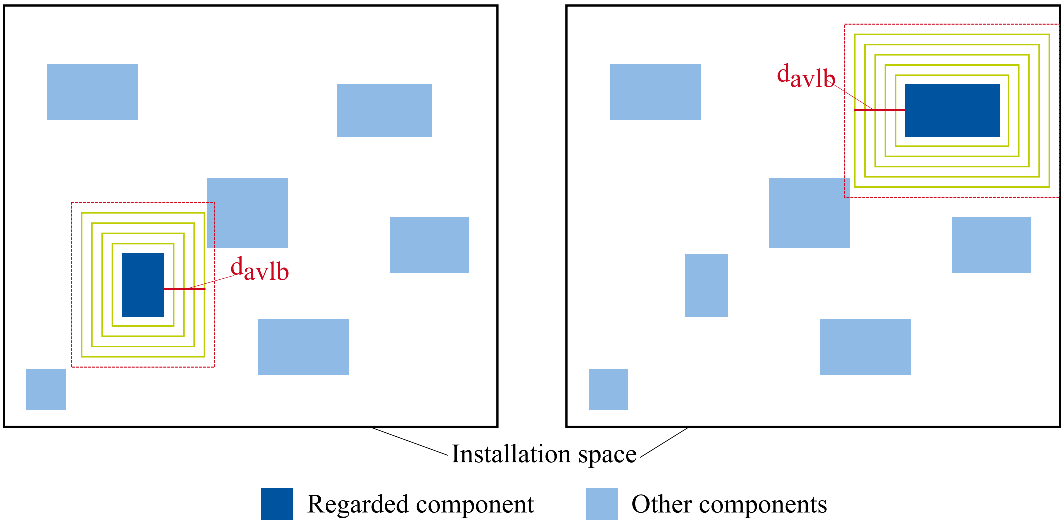


Figure 3.15: Schematic illustration of procedure used to determine the available space around a component.

Additional gradation was added taking into account the length of standard tools. Considered are a combination wrench with size 15 which has a length of 20 cm and a size 20 combination wrench with a length of 28.5 cm [25, p. 52]. To comply with the implementation, the length for a size 20 combination wrench was thereby rounded to 29 cm. A larger available space corresponds to a higher score, as the maintenance task can be more easily performed when enough space is given.

Amount of connections The more connections a component has, the more effort is required before being able to remove the component. In addition, the type of the system can also add complexity to the unfastening of the connections. Considered are hydraulic, pneumatic and electronic systems. It was decided, that the hydraulic connection is the most complex to unfasten, followed by the pneumatic connection. Both are unfastened in similar ways, but in hydraulic systems the fluid must be drained before loosening the connections, and it must be refilled afterwards [45, chapter 13.9.]. In electronic systems, the connections are generally of plug-in nature and therefor less complex in terms of unfastening than in hydraulic or pneumatic systems. As it can be seen in equation 3.19, the scoring factor for each component is equal to number of connections of the corresponding component. No additional calculations have to be performed.

$$S_{NrCon,\,i} = n_{connections,\,i} \tag{3.19}$$

The accessibility checklist is shown in table 3.10 and is based on the scoring factors, with the exception of the haptic access evaluation. This one is based on the amount of reachable component sides and the corresponding axis directions.

Score	Haptic access	Visual access	Packaging
1	0 sides	$S_{vis,\,i} = 0\%$	$S_{pack,\,i} \geq 9$
2	1 side in 1 dir.	$0\,\% < S_{vis,\,i} < 10\,\%$	$S_{pack,\,i} = 8$
3	2 sides in 1 dir.	$10\,\% \leq S_{vis,\,i} < 20\,\%$	$S_{pack,\,i} = 7$
4	2 sides in 2 dir.	$20\,\% \leq S_{vis,\,i} < 30\,\%$	$S_{pack,\,i} = 6$
5	-	$30\,\% \leq S_{vis,\,i} < 40\,\%$	$S_{pack,\,i} = 5$
6	3 sides in 2 dir.	$40\,\% \leq S_{vis,\,i} < 60\,\%$	$S_{pack,\,i} = 4$
7	4 sides in 2 dir.	$60\,\% \leq S_{vis,\,i} < 75\,\%$	$S_{pack,\,i} = 3$
8	3 sides in 3 dir.	$75\,\% \leq S_{vis,\,i} < 90\,\%$	$S_{pack,\,i} = 2$
9	4 sides in 3 dir.	$90\,\% \leq S_{vis,\,i} < 100\,\%$	$S_{pack,\,i} = 1$
10	5 or more sides	$S_{vis,\,i} = 100\%$	$S_{pack,\,i} = 0$

Score	Space around the component	Amount of connections		
		hydraulic	pneumatic	electronic
1	$S_{space,\,i} < 6\,cm$	$S_{NrCon,\,i} \geq 6$	$S_{NrCon,\,i} \geq 7$	$S_{NrCon,\,i} \geq 14$
2	-	$S_{NrCon,\,i} = 5$	$S_{NrCon,\,i} = 6$	$S_{NrCon,\,i} = 13$
3	$6\,cm \leq S_{space,\,i} < 9\,cm$	-	-	$S_{NrCon,\,i} = 12$
4	-	$S_{NrCon,\,i} = 4$	$S_{NrCon,\,i} = 5$	$S_{NrCon,\,i} = 11$
5	$9\,cm \leq S_{space,\,i} < 10\,cm$	-	-	$S_{NrCon,\,i} = 10$
6	$10\,cm \leq S_{space,\,i} < 13\,cm$	$S_{NrCon,\,i} = 3$	$S_{NrCon,\,i} = 4$	$S_{NrCon,\,i} = 9$
7	-	-	-	$S_{NrCon,\,i} = 8$
8	$13\,cm \leq S_{space,\,i} < 20\,cm$	$S_{NrCon,\,i} = 2$	$S_{NrCon,\,i} = 3$	$S_{NrCon,\,i} = 7$
9	$20\,cm \leq S_{space,\,i} < 29\,cm$	-	-	$S_{NrCon,\,i} = 6$
10	$29\,cm \leq S_{space,\,i}$	$S_{NrCon,\,i} = 1$	$S_{NrCon,\,i} \leq 2$	$S_{NrCon,\,i} \leq 5$

Table 3.10: Accessibility checklist of the self-developed procedure.

The accessibility score $C_{acc,\,i}$ for each component is found by using equation 3.20. Those scores are summarized to the overall score C_{acc} according to equation 3.21, by using the individual weighting factors W_i.

$$C_{acc,\,i} = \frac{C_{hapt,\,i} + C_{vis,\,i} + C_{pack,\,i} + C_{space,\,i} + C_{NrCon,\,i}}{5} \tag{3.20}$$

$$C_{acc} = \frac{\sum\limits_{i=1}^{n} C_{acc,\,i} \cdot W_i}{\sum\limits_{i=1}^{n} W_i} \tag{3.21}$$

3.4.3 Human Factor Checklist

In the *human factor checklist*, the properties of the system are scored based on their effect on the person performing the maintenance tasks. The scores for the necessity of overhead-working and for the size of the maintenance access are dependent on the location and size of the considered maintenance access. The score for the body posture also depends on the position of the maintenance access, as well as on the component mass, the size of the installation space and the working height. The remaining three scores of the human factor checklist are the scores for the component's mass, size and its distance to the maintenance access. Those are considered component-wise based on the individual properties.

Working overhead To determine the score for overhead working, it is checked, in which plane the maintenance access is located. The assignment of the scoring factor $S_{overhead}$ is shown in equation 3.22. If the maintenance access is placed in the x-y-plane at $z = 0$, then overhead working is necessary. For all other maintenance access locations, no overhead working is needed to perform the maintenance task. The coordinate system is placed, as mentioned before, in the lower left front corner of the installation space.

$$S_{overhead} = \begin{cases} 1, & \text{if access in x-y-plane with } z = 0 \\ 0, & \text{else} \end{cases} \tag{3.22}$$

Component mass Limits for an appropriate lifting load for a human are extracted from DGUV2019-015 [18, p. 41] and can be seen in table 3.11. They differ based on the age and gender of the person and on the lifting frequency. The scoring factor $S_{mass,\,i}$ is equal to the component mass. For the scoring, the eight different values of table 3.11 are sorted in descending order, starting with 55 kg and ending with 10 kg. Those are associated to scores 3 to 10, whereby the lowest lifting load corresponds to the highest score. The scores 1 and 2 are assigned to higher component masses than included in table 3.11. Those were chosen to add further gradation and to consider the possibility of two persons lifting the component. The exact scoring can also be seen in the human factor checklist in table 3.13.

Age	Appropriate lifting load			
	Occasional lifting (up to 2 times/h)		Frequent lifting (more than 2 times/h)	
	Women	**Men**	**Women**	**Men**
15 - 18	15 kg	35 kg	10 kg	20 kg
19 - 45	15 kg	55 kg	10 kg	30 kg
$>$ 45	15 kg	45 kg	10 kg	25 kg

Table 3.11: Limits for appropriate lifting masses based on age, gender and lifting frequency [18, p. 41].

Component size This score takes into account the ease to grab an component based on its size. It is considered how much the maintainer must spread her/his arms to be able to grab the component. The scoring is based on two positions, that are illustrated in figure 3.16. Position A can be compared to the arm posture of a person sitting at a work desk. This means, that the upper arms are parallel to the chest and the shoulder joint is therefor in a relaxed position. The elbows form an angle of 90° and the forearms are pointing away from the person. Position B has the same forearm and elbow posture, but the upper arms are now parallel to the floor. For both positions, the distance between the elbows is taken as the reference for the scoring. Those are called distance A and distance B in the following.

For both positions, the elbow-to-elbow breadth can be derived from statistical body dimensions [41, p. 137]. Thereby, the 5^{th} percentile, mean and 95^{th} percentile values are considered for both positions. The corresponding values are shown in table 3.12. The 5^{th} percentile

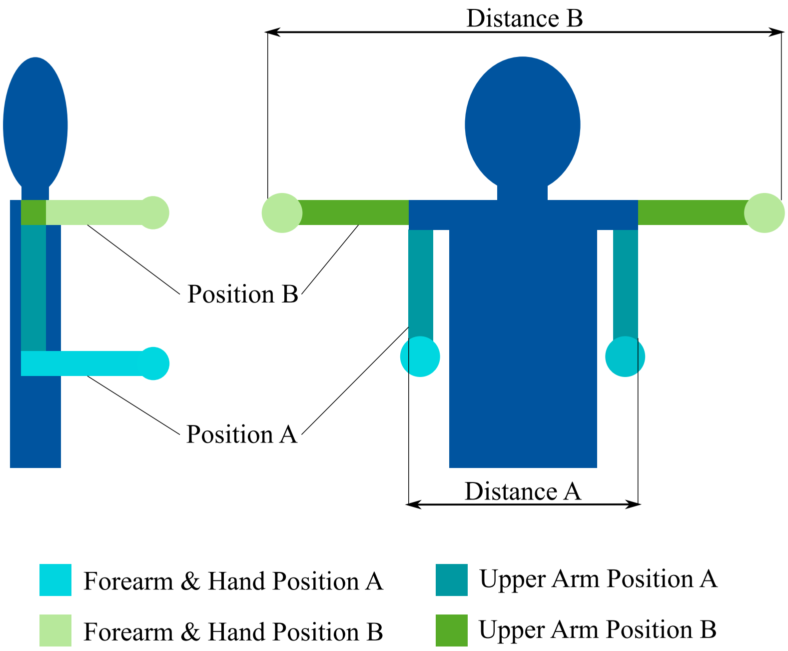


Figure 3.16: Schematic illustration of the positions A and B considered for the component size evaluation. Distance A and B correspond to the elbow-to-elbow breadth.

describes the size which is surpassed by 95% of the population, that was included in the statistical analysis. In contrary, the 95^{th} percentile value is only surpassed by 5% of the statistical population. For the scoring, position A is used to assign the scores 8, 9 and 10 and position B is used for scores 1, 2, 3 and 4. The remaining scores are a gradation between score 4 and 8. The scoring factor $S_{size,\,i}$ is equal to the biggest dimension of the component.

	Dimension A	Dimension B
5^{th} Percentile	$38\,cm$	$78\,cm$
Mean	$44\,cm$	$84\,cm$
95^{th} Percentile	$50\,cm$	$90\,cm$

Table 3.12: Considered elbow-to-elbow breadth values for position A and position B [41, p. 137].

Access size The minimum size for a maintenance access to fit one person is defined as $45\,x\,45\,cm$ [41, p. 50]. Starting from there for score 1, the size is augmented by $5\,cm$ in both directions, until reaching $85\,x\,85\,cm$ for score 10. This also corresponds to an maintenance access size large enough to fit two persons facing each other [41, p. 50]. The scoring factor $S_{AccSize}$ is defined by the smallest of the two dimensions, dim_1 and dim_2, of the regarded maintenance access. The calculation is also shown in equation 3.23.

$$S_{AccSize} = min(dim_1; dim_2) \tag{3.23}$$

Distance between component and maintenance access As depicted in figure 3.17, the distance between the component and the maintenance access is defined as the distance between the component center and the nearest maintenance access corner. The calculation of the scoring factor $S_{dist,i}$ is shown in equation 3.24, with $c_{x,i}$, $c_{y,i}$ and $c_{z,i}$ being the center coordinates of component i and a_x, a_y and a_z the coordinates of the nearest corner of the maintenance access. The scoring is again based on statistical body dimensions. In this case, the mean values for the total body length ($175\,cm$), head to knee distance ($124\,cm$), functional arm length ($82\,cm$), forearm length ($48\,cm$) and the length of a hand ($19\,cm$) are considered as limits for the scoring [41, p. 137].

$$S_{dist,i} = \sqrt{(c_{x,i} - a_x)^2 + (c_{y,i} - a_y)^2 + (c_{z,i} - a_z)^2} \tag{3.24}$$

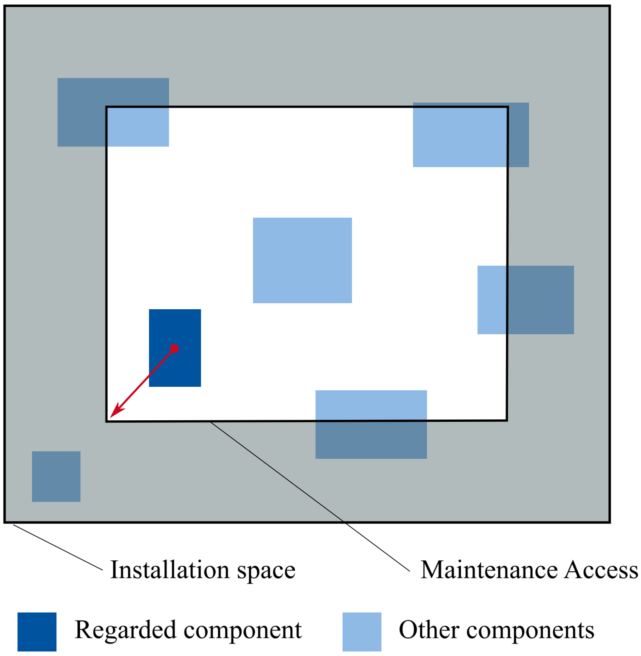


Figure 3.17: Schematic 2D-illustration of how the distance between the component and the maintenance access is defined.

Body Posture The evaluation of the body posture is based on the REBA procedure, which is explained in chapter 2.4. Within the framework of this thesis, the evaluation of the body posture is divided in three cases, based on the location of the maintenance access.

1. Maintenance access in x-z- or y-z-plane

2. Maintenance access in x-y-plane at $z = z_{max}$

3. Maintenance access in x-y-plane at $z = 0$

The three cases are also depicted in figure 3.18. The working height h_w is an input of the self-developed procedure and defines the z-wise distance between the working floor and the lower side of the installation space. The real working height $h_{w,real}$ depends on the location of the maintenance access.

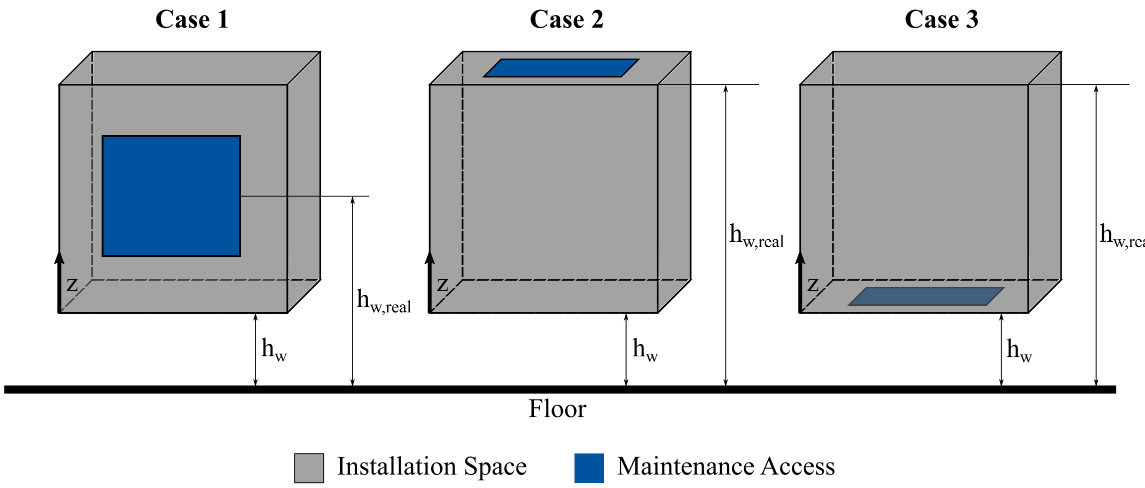


Figure 3.18: Illustration of the different maintenance access positions and the associated real working height $h_{w,\,real}$.

In case 1, it is defined as the distance in z-direction between the center of the regarded maintenance access and the floor. In case 2 and 3 it equals the distance between the floor and the upper edge of the installation space, also in z-direction. For each case, different postures based on the real working height $h_{w,\,real}$ have been evaluated and scored using the REBA methodology. The complete list of postures and associated scores can be found in appendix B in the tables B.3, B.4 and B.5. The thereby used limits for the working height are mean values of statistical body measures [41, p. 137]. If $h_{w,\,real}$ is out of reach, a lifting platform, or similar devices, must be used to perform the maintenance task. It is assumed, that the lifting platform is adjusted to allow the ergonomically most optimal body posture for the considered case. But, in this implementation, the requirement of such additional equipment is penalized with an augmentation of the final REBA score by 1 point. This height penalty is also marked in table B.3.

The load factor is defined based on the component mass, using table A.7. It is assumed, that sufficient grips and handles are provided and therefor, the coupling factor is set to 0. Another assumption is made for the activity factor, which is also set to 0. This is explained by the fact that maintenance tasks do usually not require the mechanic to be static for a long time and neither do they require small repeated movements or a rapid change of position.

As the coupling factor equals 0, score C is only dependent on the sum of score A and the load factor as well as on score B. Based on those values, score C can be determined by using table A.10. As explained in chapter 2.4, the final REBA score is equal to the sum of score C and the activity factor. Since the activity factor is assumed to be equal to 0, the final REBA score is identical with score C.

The scoring factor $S_{post,\,i}$ is equal to the final REBA score, augmented by the height penalty if the real working height is out of reach. The scoring factor is component-dependent, as the component mass defines the load factor.

The scoring of the properties defining the human factor is performed using table 3.13. As before, component-dependent properties, marked with index i, are scored for each component individually.

Score	Working Overhead	Component Mass	Component Size
1	$S_{overhead} = 1$	$100\,kg < S_{mass,\,i}$	$90\,cm < S_{size,\,i}$
2	-	$55\,kg < S_{mass,\,i} \leq 100\,kg$	$84\,cm < S_{size,\,i} \leq 90\,cm$
3	-	$45\,kg < S_{mass,\,i} \leq 55\,kg$	$78\,cm < S_{size,\,i} \leq 84\,cm$
4	-	$35\,kg < S_{mass,\,i} \leq 45\,kg$	$70\,cm < S_{size,\,i} \leq 78\,cm$
5	-	$30\,kg < S_{mass,\,i} \leq 35\,kg$	$60\,cm < S_{size,\,i} \leq 70\,cm$
6	-	$25\,kg < S_{mass,\,i} \leq 30\,kg$	$55\,cm < S_{size,\,i} \leq 60\,cm$
7	-	$20\,kg < S_{mass,\,i} \leq 25\,kg$	$50\,cm < S_{size,\,i} \leq 55\,cm$
8	-	$15\,kg < S_{mass,\,i} \leq 20\,kg$	$44\,cm < S_{size,\,i} \leq 50\,cm$
9	-	$10\,kg < S_{mass,\,i} \leq 15\,kg$	$38\,cm < S_{size,\,i} \leq 44\,cm$
10	$S_{overhead} = 0$	$S_{mass,\,i} \leq 10\,kg$	$S_{size,\,i} \leq 38\,cm$

Score	Access Size	Distance Component <-> Access	Body Posture
1	$S_{AccSize} < 45\,cm$	$175\,cm < S_{dist,\,i}$	$S_{post} \geq 12$
2	$45\,cm < S_{AccSize} \leq 50\,cm$	$124\,cm < S_{dist,\,i} \leq 175\,cm$	$S_{post} = 11$
3	$50\,cm < S_{AccSize} \leq 55\,cm$	-	$S_{post} = 10$
4	$55\,cm < S_{AccSize} \leq 60\,cm$	-	$S_{post} = 9$
5	$60\,cm < S_{AccSize} \leq 65\,cm$	-	$S_{post} = 8$
6	$65\,cm < S_{AccSize} \leq 70\,cm$	$82\,cm < S_{dist,\,i} \leq 124\,cm$	$S_{post} = 7$
7	$70\,cm < S_{AccSize} \leq 75\,cm$	-	$S_{post} = 6$
8	$75\,cm < S_{AccSize} \leq 80\,cm$	$48\,cm < S_{dist,\,i} \leq 82\,cm$	$S_{post} = 5$
9	$80\,cm < S_{AccSize} \leq 85\,cm$	$19\,cm < S_{dist,\,i} \leq 48\,cm$	$S_{post} = 4$
10	$85\,cm < S_{AccSize}$	$19\,cm < S_{dist,\,i}$	$S_{post} \leq 3$

Table 3.13: Human factor checklist of the self-developed procedure.

For the human factor checklist, the component-wise results are calculated according to equation 3.25. Once again, those score are combined to the human factor score of the system by using a weighted sum, as shown in equation 3.26.

$$C_{HF,\,i} = \frac{C_{overhead} + C_{mass,\,i} + C_{size,\,i} + C_{AccSize} + C_{dist,\,i} + C_{post,\,i}}{6} \tag{3.25}$$

$$C_{HF} = \frac{\sum_{i=1}^{n} C_{HF,\,i} \cdot W_i}{\sum_{i=1}^{n} W_i} \tag{3.26}$$

3.5 Optimization

The optimization procedure aims at improving the system's maintainability by changing the position of the components and modules within certain boundaries.

The input for the optimization is the system and the associated maintainability prediction output of either Procedure III or the self-developed procedure. Two different boundary conditions (BC) are applied. The first one is linear and defines the upper and lower limits in each axis direction. The second one is a non-linear BC to avoid that the optimizer places the components within each other.

The **linear BC** are defined by the values of the allowed movement $\Delta_{allowed}$, which are set in the component properties. The calculation for the lower boundary (LB) of the position of component i are shown in equation 3.27. The allowed movement values are subtracted from the component position values in the corresponding axis direction. To ensure that the component is placed within the installation space, the maximum of the calculated value and zero is taken. This is deduced from the fact that the installation space is always placed in the axis origin at (0,0,0).

$$\begin{aligned} LB_{x,\,i} &= max(x_{pos,\,i} - \Delta_{allowed,\,x,\,i}\,;\,0) \\ LB_{y,\,i} &= max(y_{pos,\,i} - \Delta_{allowed,\,y,\,i}\,;\,0) \\ LB_{z,\,i} &= max(z_{pos,\,i} - \Delta_{allowed,\,z,\,i}\,;\,0) \end{aligned} \tag{3.27}$$

The upper boundary (UB) is defined in equation 3.28. Similar to the calculation of the LB, the first part corresponds to the addition of the component position and the allowed movement. However, for the consideration of the installation space limits, the component dimension must also be taken into account. This is due to the fact, that the component position defines the corner of the component that faces the axis origin. The ultimate possible component position is therefor defined as the subtraction of the maximum component space dimension and the component dimension.

$$\begin{aligned} UB_{x,\,i} &= min(x_{pos\,i} + \Delta_{allowed,\,x,\,i}\,;\,x_{max,\,space} - x_{dim,\,i}) \\ UB_{y,\,i} &= min(y_{pos\,i} + \Delta_{allowed,\,y,\,i}\,;\,y_{max,\,space} - y_{dim,\,i}) \\ UB_{z,\,i} &= min(z_{pos\,i} + \Delta_{allowed,\,z,\,i}\,;\,z_{max,\,space} - z_{dim,\,i}) \end{aligned} \tag{3.28}$$

The **non-linear BC** ensures that the optimizer does not place different components within each other. This is performed using arrays, which are constructed as described in chapter 3.1.1. Each entry in the array corresponds to $1\,cm^3$ of the installation space. If a component is placed in the correspondent volume, the array value corresponds to the component number. Else, the array value equals zero. For the non-linear BC, the array is filled with all components except for the one that is currently optimized. After the array is created, it is checked, if the volume defined by the optimized component position is occupied by other components or not. If it is free, the return value of the function will be zero and the BC is fulfilled.

The optimization is performed for each component individually, in the same order as they are saved in the *system* variable. The **surrogate optimization** [34] of MATLAB's Global Optimization Toolbox is chosen as the optimization algorithm for this implementation. This algorithm performs a global optimization using random initial points. It is chosen over other global optimizations as it takes into account lower and upper boundaries as well as non-linear BC, while minimizing the value of the objective function. Additionally, an integer condition can be applied, which obliges the optimizer to only use integer values for the optimization variable. This is necessary in the context of this implementation, as only integer component position values can be used for the evaluations. Detailed information of the used surrogate algorithm can be found in [52].

As aforementioned, the algorithm minimizes the function value. Therefor, the **objective function** f_{obj}, shown in equation 3.29, is corresponding to the subtraction of the maximum possible maintainability score $C_{max,proced}$ and the calculated score C_{proced} for both procedures. The final score for the self-developed methodology C_{total} has values between 0 and 10 and is therefor subtracted from its maximum value 10. For Procedure III, the sum of the automatically evaluated scores is considered and subtracted from its maximum value of 52.

$$f_{obj} = C_{max,proced} - C_{proced} \tag{3.29}$$

The optimization procedure stops when the global minimum is found or when the number of function evaluations reaches the predefined limit e_{max}. This limit can be set in the optimization options.

This chapter served to describe the implementation of the methodologies, which are used to generate the results in the following chapter 4. First, the input system was described. It consists of the installation space and the components, which can optionally be combined in modules. The properties for both, the installation space and the components, are also explained in detail. For this thesis, a part of the hydraulic system of a Boeing 777 is used as the reference system.
For Procedure III of MIL-HDBK-472, a simple and a complete approach are implemented. Both have the automatic evaluation of the accessibility questions in common but they differ in the way how the remaining questions are answered. The implementation of the accessibility questions highlighted the downsides of Procedure III. Therefor, another maintainability prediction was developed.
The self-developed procedure, was described in detail in this chapter. It is composed of three checklists containing 14 different system properties, that are evaluated on a scoring scale between 1 to 10. The different scoring scale, compared to Procedure III, was chosen to allow a more accurate scoring of the maintainability. The geometry checklist thereby considers if the component fits through the access opening, the occupied volume and the distance between connected components. All those properties are not considered in Procedure III. Further system properties are comprised in the accessibility and the human factor checklist. Concerning the accessibility, the packaging, the haptic and the visual access are analyzed in the same way as for Procedure III, but the scoring is performed differently to enable a larger differentiation. The other two properties of the accessibility checklist are the space around the component and the amount of connections. The human factor checklists comprises six different properties all concerning the effect of the maintenance task on the mechanic performing it. Beside the component mass, which is also considered in Procedure III, this checklist also takes into account the need to work overhead, the component size, the distance to the maintenance

access, the size of the maintenance access and the body posture during the maintenance task. All the considered properties can be evaluated objectively and automatically based on the provided inputs. This is another advantage of the self-developed maintainability prediction compared to Procedure III. Furthermore, the considered properties allow to take into account the trade-off between conflicting properties.

The optimization procedure was also describe. A surrogate optimization is used to augment the system's maintainability by changing its architecture. Thereby, predefined boundaries are respected.

4 Results

The results obtained from the application of Procedure III and of the self-developed maintainability prediction to the reference system are presented in this chapter. For both maintainability prediction methodologies, the system is also optimized with regard to higher maintainability scores. A comparison between the initial and the optimized system is further shown. The self-developed procedure includes a checklist weighting as well as a component-dependent weighting. Both are considered for the maintainability prediction and the optimization of the reference system. Furthermore, a condensed version of the reference system is described in chapter 4.2. Both procedures are applied to this system and optimizations are also performed.

It should be noted, that only the results that are necessary to understand the argumentation are presented in this chapter. A complete overview of the results and the associated system architectures is given in appendix C.

4.1 Reference System

The reference system is implemented and modularised as described in chapter 3.1.4. An overview of the components, the associated component numbers and component properties is shown in table 4.1. In the following, the components will be referenced by their number. The term ‘components’ includes also the modules, as only the modularized system is regarded.

Nr.	Name	Dimension (x, y, z) $[cm]$	Mass $[kg]$	Nr. of Connections	Connected Components
10001	Reservoir Pressurization Module	$(34, 6, 15)$	6.66	3	1, 7
10002	Return Filter Module	$(20, 10, 10)$	7.304	2	9
10003	ACMP Filter Module	$(20, 30, 25)$	9.2	6	12
1	Reservoir Shut-Off Valve	$(4, 6, 8)$	0.15	2	10001
7	Reservoir Pressure Switch	$(3, 3, 9)$	0.113	1	10001, 8
8	Reservoir Pressure Relief Valve	$(4, 4, 8)$	0.0998	1	7, 9
9	Reservoir	$(37, 37, 37)$	28.57	5	10002, 8, 10, 11, 12
10	Sample Valve	$(8, 6, 4)$	0.15	1	9
11	Drain Valve	$(4, 6, 8)$	0.15	1	9
12	AC Motor Pump	$(23, 49, 23)$	10	3	10003, 9

Table 4.1: Component list of the reference system with modules.

The reference system is shown in figure 4.1 as a projection in the xy-plane,viewed from $z = 0$. This illustration allows a more comprehensible visualization of the correlations between the components and the installation space. This can be especially helpful to understand the scores for packaging or haptic and visual access. The associated component positions are presented in table C.1 in appendix C.

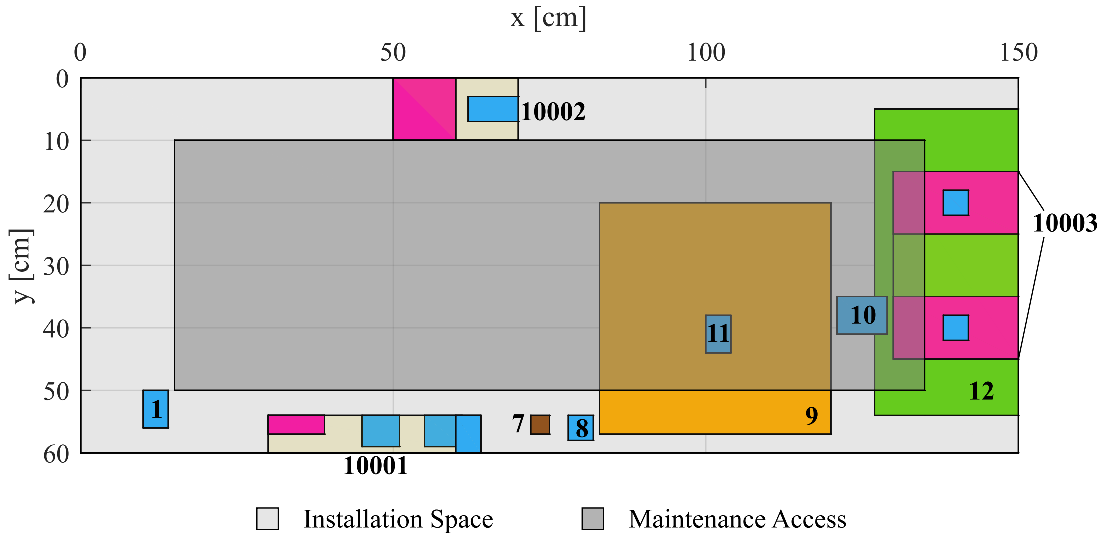


Figure 4.1: Reference system projected in the xy-plane, viewed from $z = 0$.

4.1.1 MIL-HDBK-472 Procedure III and Allocation

Maintainability Prediction

As the focus is put on evaluating the accessibility of the system, Procedure III is performed using the simple approach. As explained in chapter 3.2, the difference between the simple and the complete approach is the scoring of the not-automatically evaluated questions. When using the simple approach, the user must choose values for the summarized scores $C_{A,simple}$, $C_{B,simple}$ and $C_{C,simple}$ as well as one number for the steps of removal, that will be used for every component. In contrary to this, when using the complete approach it is necessary to answer each of the not-automatically evaluated questions individually and for each component.

The summarized scores of the non-automatically evaluated scores are set to 75% of their maximum values. This results in $C_{A,simple} = 39$, $C_{B,simple} = 15$ and $C_{C,simple} = 3$. It is assumed, that four steps are required for the removal of one component and that the maintenance task is performed by an all-male crew. For the maintenance allocation, a semi-automatic fault isolation technique is assumed, meaning that k_{j2} is equal to 2. The MTTR is calculated based on the mean of the MCT values.

As all required inputs are declared, the maintainability prediction can be performed. The overall accessibility percentage for the reference system is equal to 71.73%. In order to be able to classify this result, the accessibility percentage is also calculated for the landing gears of a Jetstream 31 and of a BAe 146-300. Both are scored using Procedure III by Bin Wan Husain [6, p.104, p.118]. The analysis of the scores for the Jetstream 31 landing gear [6, p.118] leads to an accessibility percentage of 39.38%. The low value mainly results from the packaging score C_{A5}, which is equal to 0 for all components. Furthermore, the step-dependent scores of checklist C are equal to 0 for 14 of the 18 components. Bin Wan Husain scored the BAe 146-300 landing gear by using the original version of checklist C and not his adaptation. However, the scores [6, p.104] can still be combined to an accessibility percentage, which is equal to 68.11%. Compared to those two systems, the here considered reference system has the highest accessibility percentage. The value of 71.73% is in the same range as the accessibility percentage of the BAe 146-300 landing gear.

The following table 4.2 includes the automatically evaluated scores for each component of the reference system. It can be seen, that the internal access (A4) is not equal to the ideal score $C_{A4} = 4$ for five of the ten components. When looking at the system in figure 4.1, it can be seen that the components with $C_{A4} = 2$ are all placed fully outside of the maintenance access. From this results, that the visual access is not given for those components. As their score C_{A4} is equal to 2, it can be concluded, that the manipulative access is given. If this would not be the case, the score would be 0. The remaining components have a score C_{A4} equal to 4, which means, that manipulative and visual access are given. It follows, that all components are haptically accessible but only five of the ten components are visually accessible. As mentioned in chapter 3.2, the terms 'haptic' and 'manipulative' have the same meaning.

Nr.	C_{A4}	C_{A5}	C_{B3}	C_{B6}	C_{C1}	C_{C2}	C_{steps}	Accessibility Percentage
10001	2	4	4	4	3	4	3	80.77
10002	2	4	4	4	3	4	3	80.77
10003	4	0	4	4	3	3	1	48.08
1	2	4	4	4	3	4	3	80.77
7	2	4	4	4	3	4	3	80.77
8	2	4	4	4	3	4	3	80.77
9	4	2	4	4	3	1	2	61.54
10	4	4	4	4	3	4	3	84.62
11	4	4	4	4	3	4	3	84.62
12	4	0	4	4	3	3	0	34.62

Table 4.2: Automatically evaluated accessibility scores of Procedure III for the reference system.

The packaging score C_{A5} for component 10003 is equal to 0, which can be explained by the fact, that two other components, 9 and 10, must be removed to gain access to the component. To access component 9, one other component must be removed, resulting in $C_{A5} = 2$ for component 9. The special case for components that do not fit through the maintenance access without being turned is applied to component 12. It is assumed that all other components must be removed in order to have enough space to turn the component. The packaging also influences the score C_{steps}, as the total number of disassembly steps is dependent on the number of components to be removed.

The score C_{B3} for additional equipment and the score C_{B6} for the required personnel are equal to 4 for all components. This is due to the fact that no component mass is larger than $30\,kg$, which is the maximum mass to be lifted by one male person. For score C_{C1}, concerning the arm, leg and back strength, the assigned load factor F_L is also dependent on the component mass. The values for F_L are between 1 and 4 for this system, resulting in values for F_{total} between 12 and 18. This is achieved by using the assumed values for F_T, F_P and F_E, as presented in chapter 3.2. If F_{total} has a value between 10 and 22, the score C_{C1} equals 3. This is the case for every component of the reference system.

Finally, the score C_{C2} for endurance and energy is also defined by the component mass. It equals 4 if the component mass is less than $8\,kg$, which is the fact for all components except for 10003, 9 and 12. Components 10003 and 12 have a mass between 8 and $15\,kg$ and therefor a score of 3 for question C2. Equally, component 9 has a score of 1 due to its mass being between 23 and $40\,kg$.

The accessibility percentage values are calculated by dividing the sum of the achieved scores by the sum of the maximum possible scores, which is equal to 52. It can be seen in table 4.2, that the largest accessibility percentage of 84.62% is attained for components 10 and 11. This meets the expectations, as both components are relatively small and light, feature full visual and manipulative access and can be removed without having to remove other components. On the other hand, components 10003 and 12 stand out negatively with accessibility percentage values of 48.08% and 34.62% respectively. This can be reasoned considering that both components require multiple disassembly steps. Additionally, they have larger dimensions and they are heavier compared to most of the other components of the reference system.

The predicted MCT values are compared to the allocated maintenance times R_{pj} in figure 4.2. It can be seen, that the predicted maintenance times are higher compared to the allocated maintenance times for every component of the reference system. From this follows, that there is the need to improve the maintainability of the system. But it should also be noted, that both, the maintainability prediction and allocation have flaws when being used without detail knowledge of the used system. The MCT values of Procedure III should be regarded with caution, especially for the here considered simple approach, as this uses assumed values for the sum of the not-automatically evaluated scores. Those values have an influence on the resulting MCT. Therefor, a tendency for the maintenance time can be deduced from the MCT values, but the times should not be regarded as precise predictions of the true maintenance time.

Using the complete approach would lead to a more accurate evaluation, but it is only applicable if the required detailed information about the system is provided. The accuracy of the

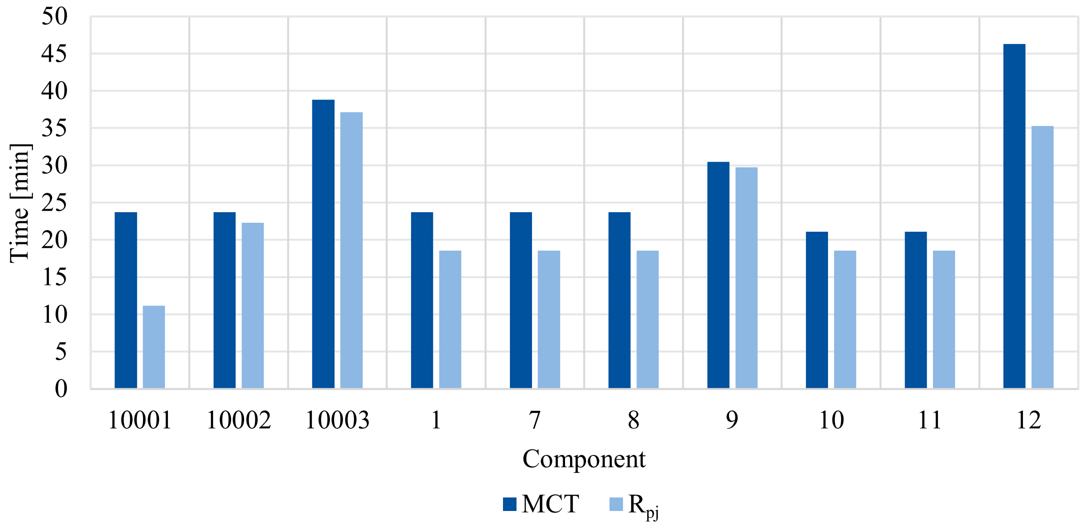


Figure 4.2: Comparison between the predicted maintenance time MCT and the allocated maintenance time R_{pj} for the reference system and $k_{j2} = 2$.

complete approach cannot be assessed for the here considered reference system. On the one hand, the detailed information to thoroughly answer the questions of Procedure III is not provided, thus the MCT cannot be predicted accurately. On the other hand, information about the real maintenance times must also be known as a comparative value to the MCT. However, Bin Wan Husain compared the MCT values for a Jetstream 31 landing gear [6, p. 116 ff.] to the respective billing times, provided by a MRO company. The billing times include, in addition to the time for repair and replacement, also time for the functional test and for unforeseen circumstances. Those two are not included in the MCT, but they were approximated by Bin Wan Husain and added to the MCT values to allow the comparison to the billing times. From his evaluation follows, that the MCT values are in the same range as the billing times, but they do differ by up to 26.07%. Bin Wan Husain noted, that the billing times might also contribute to this difference, as they do not correspond to the actual maintenance time, but only to the industry standard for quantifying the maintenance time. His conclusion was, that the MCT prediction is 'viable and useful' [6, p. 117], but that further validation with measured actual maintenance times could be performed in the future. [6, p. 116 ff.]

For the allocation, it can be seen in figure 4.3 that changing one variable, for example the fault-isolation factor k_{j2} from 2 (semi-automatic) to 0 (automatic), already results in different values. Now, the MCT is below the R_{pj} for components 10003 and 9. This shows, that the comparison between allocated and predicted maintenance time should only be considered as an indication to evaluate the need of design changes if enough information is provided. As this is not the case for the here presented reference system, the maintainability allocation will not be further considered.

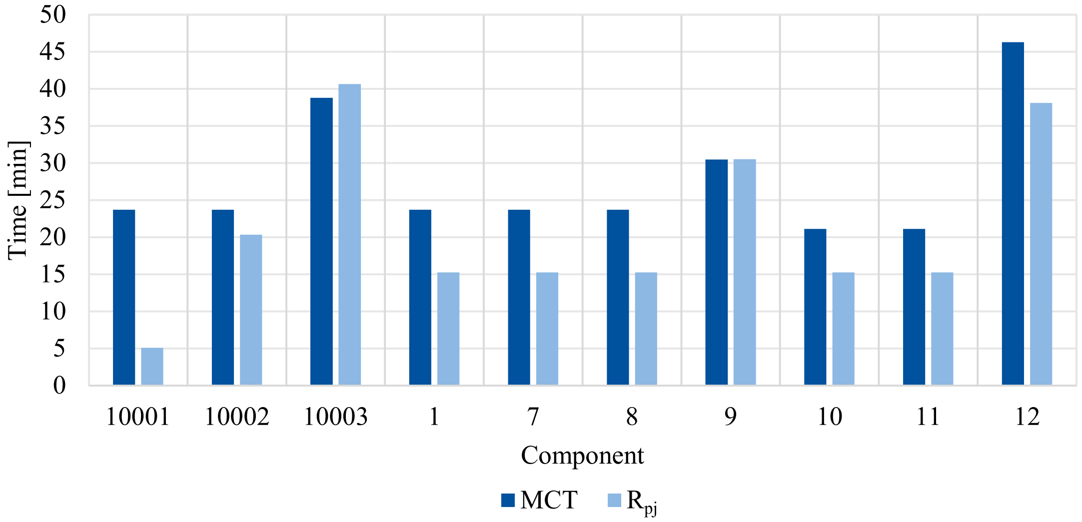


Figure 4.3: Comparison between the predicted maintenance time MCT and the allocated maintenance time R_{pj} for the reference system and $k_{j2} = 0$.

Optimization

The reference system is optimized regarding an enhanced maintainability with the optimization procedure described in chapter 3.5. The maximum function evaluations are set to $e_{max} = 200$, which is the standard value for MATLAB's surrogate optimization. To determine a reasonable allowed movement range, the optimization was performed for different $\Delta_{allowed}$ values between $5\,cm$ and $150\,cm$, which equals the largest dimension of the installation space. The resulting optimization successes are shown, as a function of $\Delta_{allowed}$, in figure 4.4. The optimization success describes the increase of the accessibility percentage compared to the value for the reference system before optimization.

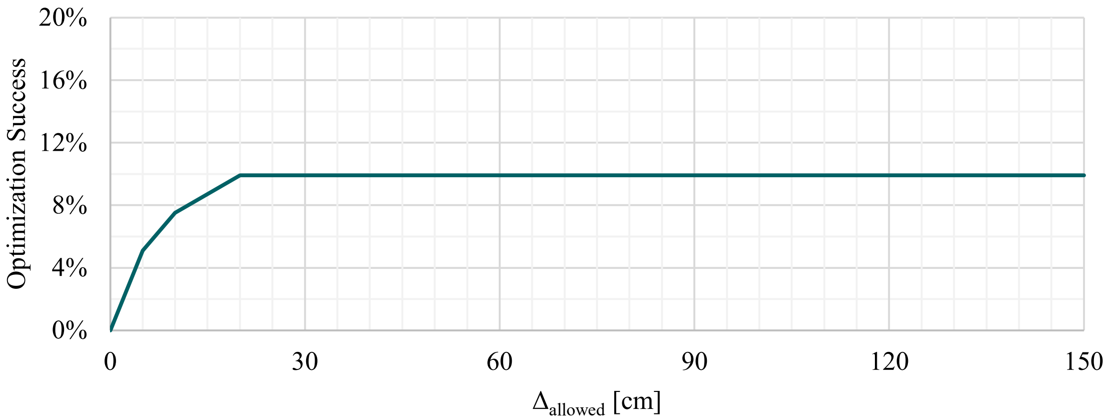


Figure 4.4: Optimization success compared to the reference system as a function of $\Delta_{allowed}$. Optimization performed with regard to Procedure III and $e_{max} = 200$.

The highest optimization success of 9.93% is achieved for $\Delta_{allowed} = 20\,cm$ and for all larger values of $\Delta_{allowed}$. Due to this, the following considerations all take into account on the system after optimization with $\Delta_{allowed} = 20\,cm$ for each component and in each axis direction.

It is remarked, that the allowed movement range can also be, as explained in chapter 3.1.1, set for each component and in each axis direction individually. It is recommended to take into account the largest technically feasible movement for each component, if the knowledge about the system is sufficient to allow such consideration.

The allowed movement $\Delta_{allowed}$ is set for all components to $20\,cm$ in each direction. The maximum function evaluations limit e_{max} of the surrogate optimization is set to 200. A comparison of the initial reference system and the optimized system is shown in figure 4.5. It is noticeable, that the components 1, 7, 8, 10001 and 10003 are moved towards the maintenance access and are partially or fully placed within. This is not the case in the initial reference system.

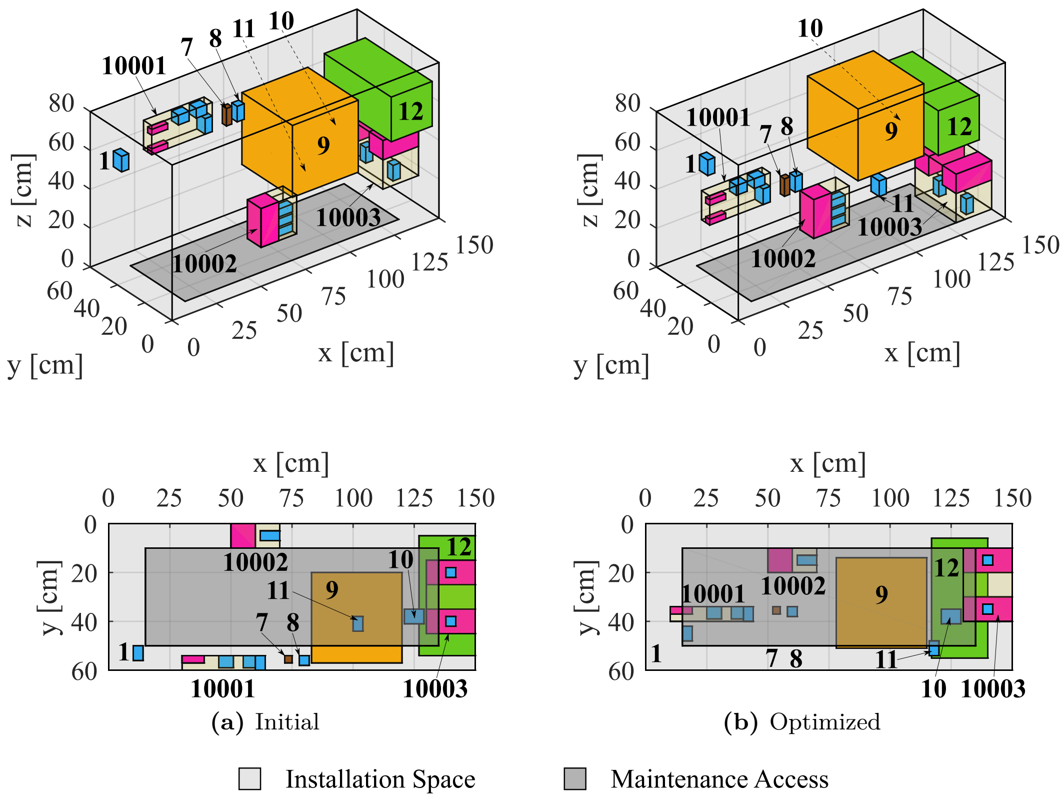


Figure 4.5: Comparison of the initial reference system (a) and the system after optimization (b) with regard to Procedure III. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

The overall accessibility percentage is increased by 9.93%, compared to the initial reference system, to 78.85%. Not every of the automatically evaluated scores can be influenced by the optimization. For instance, all scores that are dependent on the component mass cannot be ameliorated by changing the system architecture. Therefor, only the scores for question A4, A5 and the step-dependent questions of checklist C can be improved by the optimization. For those questions, the scores for both, the initial and the optimized system, are compared in figure 4.6.

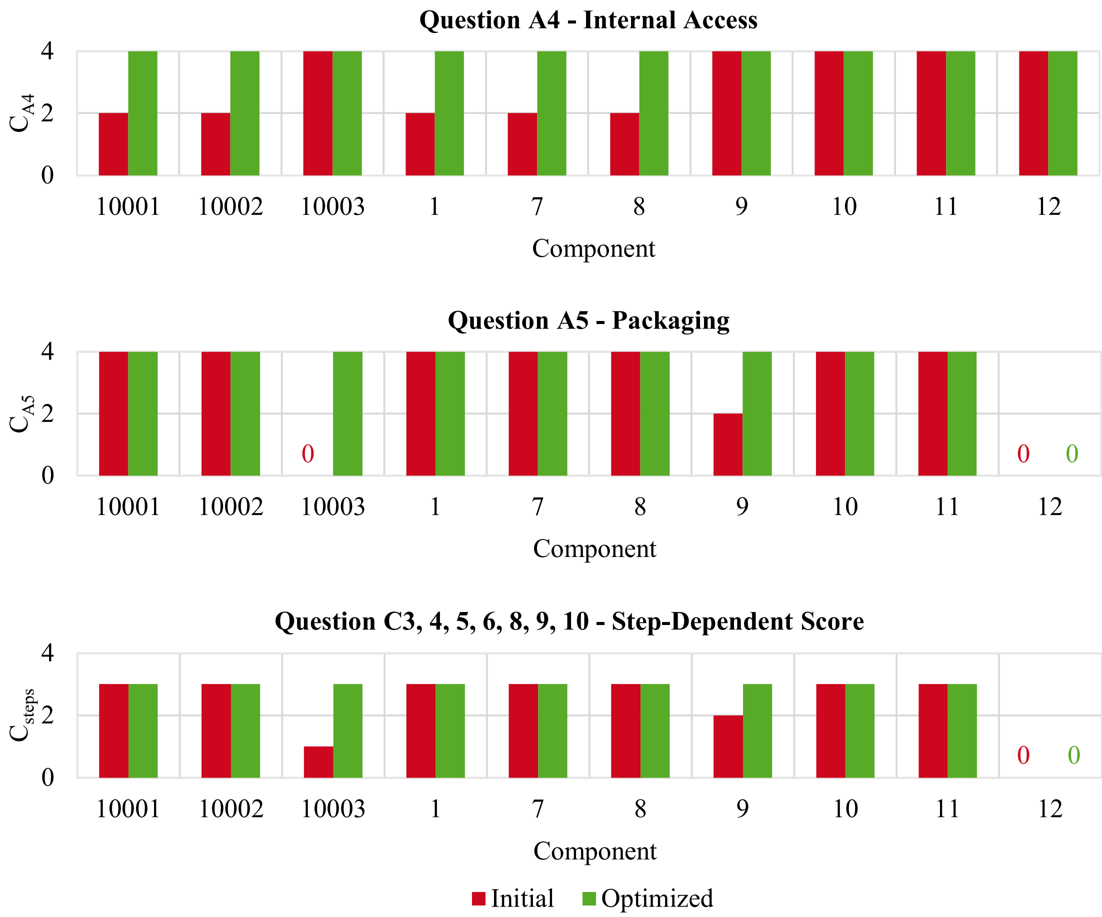


Figure 4.6: Comparison of the scores C_{A4}, C_{A5} and C_{steps} of Procedure III for the initial reference system and the optimized system. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

The scores for the initial reference system are thereby illustrated in red and those for the optimized system in green. It can be seen, that the internal access score C_{A4} is equal to its optimal value of 4 for all components. This is due to the fact, that now all components are haptically and visually accessible. The components 10003 and 9 can be removed without having to remove other components, resulting in a packaging score C_{A5} of 4. For component 12, this score cannot be increased because the component does not fit through the maintenance access without being turned and therefor it is assumed, as mentioned in chapter 3.2, that all other components must be removed. The score C_{steps} also depends on the packaging as it is based on the required removal steps. Therefor, the same trend can be seen for those scores.

In summary, it can be said that C_{A4} and C_{A5} are equal to the highest achievable value for all components. The same accounts for the step-dependent score C_{steps}, although it just has a value of 3 and not the optimal score of 4. This is due to the fact, that the steps required to remove one component are set to 4 in this context. This results, according to table A.5, in $C_{steps} = 3$ if no additional component needs to be removed. As aforementioned, the packaging and step-dependent scores C_{A5} and C_{steps} cannot be improved for component 12 and they are therefor equal to the highest here achievable value. From this follows, that all scores are equal to the respective maximum achievable values for this reference system. The optimization attained all feasible improvements.

The lowest and highest accessibility percentages are still 34.62% and 84.62%, but some intermediate values significantly improved. A comparison of the accessibility percentage per component before and after optimization is shown in figure 4.7. The largest improvement of 71.98% is achieved for component 10003, which had an accessibility percentage of 48.08% before optimization and 82.69% afterwards.

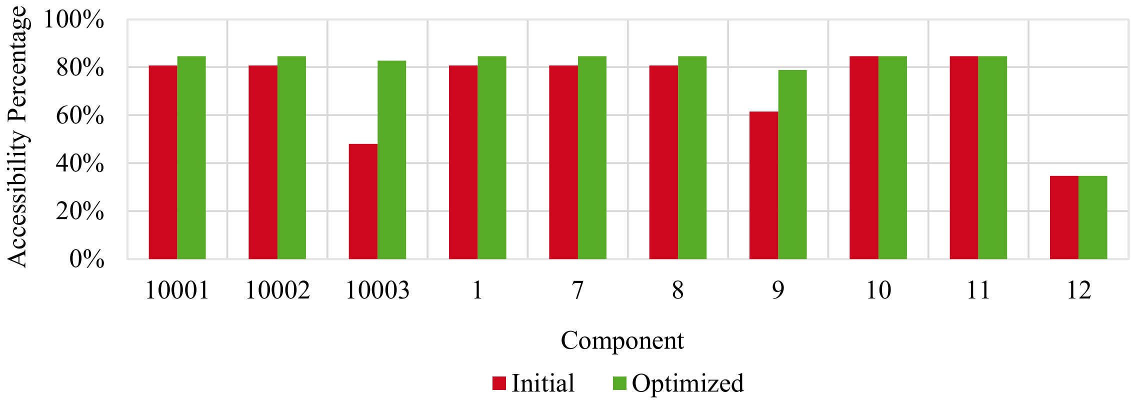


Figure 4.7: Comparison of the accessibility percentage of Procedure III for the components of the reference system and the optimized system. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

The mean corrective maintenance time MCT depends on the scores of the three checklists, whereby higher scores lead to a lower MCT. Therefor, the trend that is seen for the accessibility percentage, is seen in an opposing way for the MCT. As it can be seen in figure 4.8, the largest reduction of MCT, and thus the biggest maintainability improvement, is attained for component 10003. For this component, the predicted maintenance time is reduced from $38.80\,min$ to $21.64\,min$, which corresponds to a reduction of 44.23%. In total, $37.61\,min$ of predicted maintenance time is saved by the optimization.

The downside of the limited scoring range between 0 and 4 of Procedure III is manifested by the results. For example, the scoring does not make a difference, in terms of visual access, between components that are placed fully or partially within the maintenance access. However, from a maintenance point of view, it is very much a difference if the component is completely visible or not, especially for visual inspections. Also, it does not consider the distance between the components or other more specific properties concerning the accessibility, like the amount of connections or the restricted installation space.

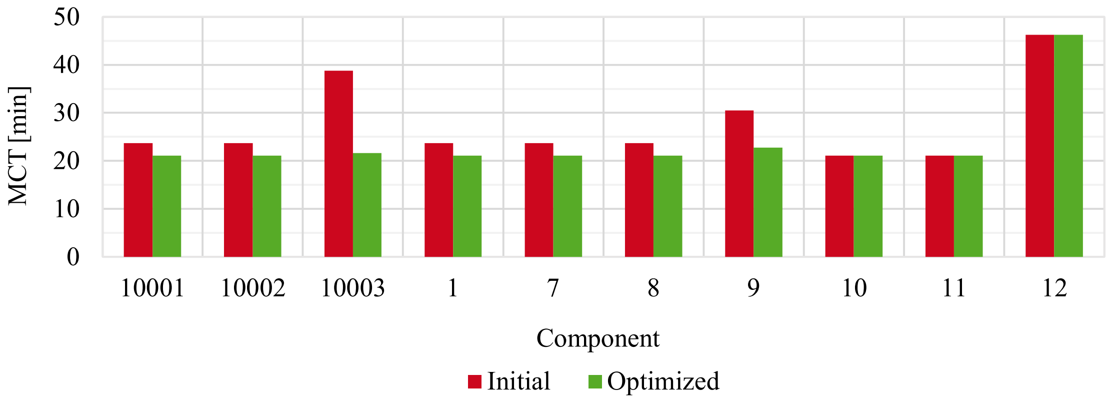


Figure 4.8: Comparison of the predicted mean corrective maintenance time MCT for the components of the reference system (red) and the optimized system (green). Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

4.1.2 Self-Developed Procedure

Maintainability Prediction

At first, the self-developed maintainability prediction is applied to the reference system without using the checklist weighting or the component weighting. The overall score C_{total} for the reference system, is equal to 6.68. Thereby, the scores for the checklists are $C_{geo} = 7.63$, $C_{acc} = 6.26$ and $C_{HF} = 6.13$. Further insight into the composition of those scores can be obtained from the component-wise scores in table 4.3.

Nr.	$C_{Geo,\,i}$	$C_{Acc,\,i}$	$C_{HF,\,i}$	$C_{total,\,i}$
10001	7.67	6.00	6.17	6.61
10002	7.00	6.00	6.17	6.39
10003	7.67	4.80	6.33	6.27
1	7.67	6.40	6.33	6.80
7	8.00	6.40	6.33	6.91
8	8.00	6.40	6.33	6.91
9	7.67	6.00	5.17	6.28
10	7.67	8.20	6.50	7.46
11	8.00	8.20	6.50	7.57
12	7.00	4.20	5.50	5.57

Table 4.3: Scores of the three checklists and the total score of the self-developed procedure for each component of the reference system.

The highest score 7.57 is achieved for component 11 and the lowest score 5.57 is achieved for component 12. The detailed property scores for the self-developed maintainability prediction are compared for those two components in figure 4.9. This allows to further comprehend the influences considered in the self-developed procedure.

It can be seen in figure 4.9, that component 12 (ACMP) has lower values compared to component 11 (drain valve) in every component-dependent score. The largest difference exists thereby for the packaging score. Component 11 has the best possible score of 10, which

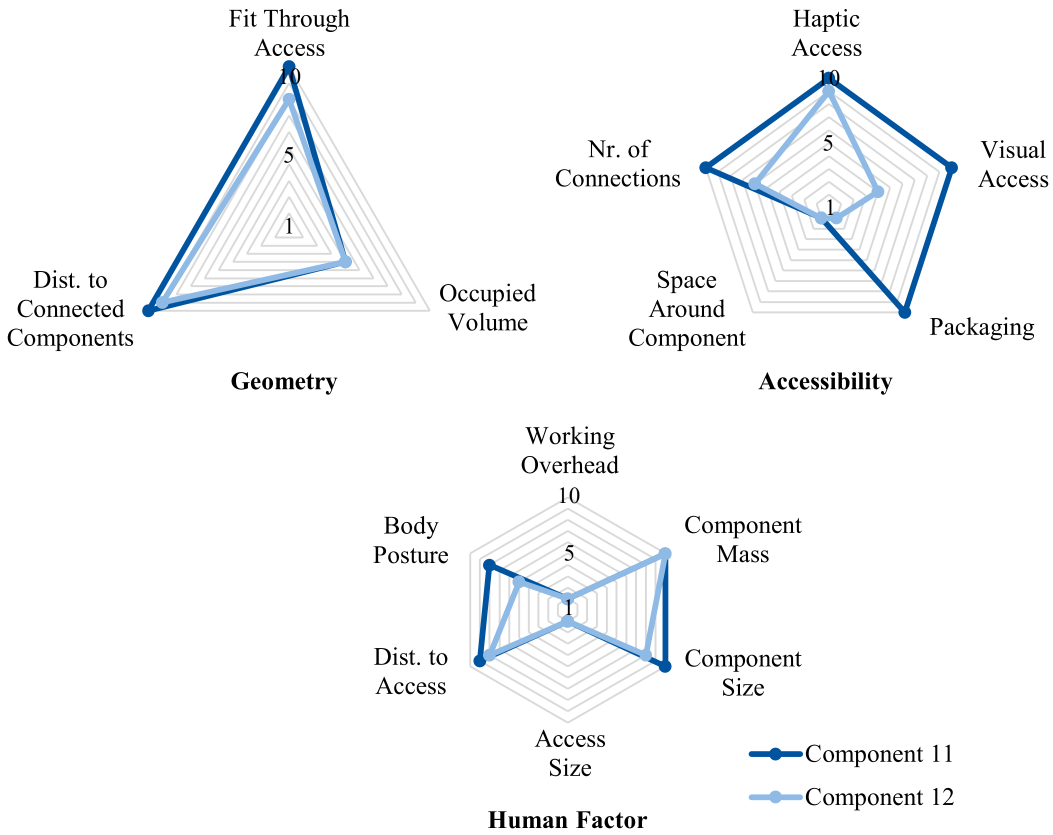


Figure 4.9: Comparison of the detailed scores of the self-developed maintainability prediction, without weighting, for component 11 (dark blue) and component 12 (light blue) of the reference system.

means that no other component must be removed. In contrary, component 12 has a packaging score of 1, as the special case for components that cannot be removed without being turned, comes into effect. The visual access score of component 12 is equal to 4 as only 28.39% of the component surface are visible when looking straight through the maintenance access. This can also be seen in the 2D-illustration of the reference system in figure 4.1.
The score for the space around the component is equal to $C_{space,\,i} = 1$ for component 11 and 12 as both have less than 6 cm of free space around them. The haptic access score for component 12 is equal to 9, which means that the component is accessible from four sides in three axis-directions, considering only the relation to the installation space housing. Component 11 is reachable from all six sides and has therefor a score of 10. The number of connections is also different for components 11 and 12. The first one has just one connection and the second one has three connections, which leads to the different scores $C_{NrCon,\,11} = 10$ and $C_{NrCon,\,12} = 6$.

In the geometry checklist, the fit through access score is equal to 8 for component 12, as it does only fit through the maintenance access after being turned.
Regarding the distance to connected components, component 11 is only connected to component 9 and has a scoring factor of $S_{ConLength,\,11} = 9.48\%$. The associated calculations are explained in equations 3.13 and 3.14. Component 12 is connected to components 10003 and

9 and has a scoring factor of $S_{ConLength,\,12} = 15.52\%$, resulting in a score of 9 according to the geometry checklist in table 3.9.

The different body posture scores can be explained by the mass of the components. Component 11 has a mass of $0.15\,kg$ and has therefor a REBA load factor of 0. On the other hand has component 12 a mass of $10\,kg$ and thus its REBA load factor is equal to 2. Together with the posture scores A and B, which can be found in table B.3, this results in a total REBA score of 5 for component 11 and of 8 for component 12. According to the human factor checklist in table 3.13, those values are transformed to $C_{post,\,i} = 8$ for component 11 and $C_{post,\,i} = 5$ for component 12.
However, despite the different component masses, both components have the same score $C_{mass,\,i} = 10$. This is due to the fact, that both masses are lower or equal to $10\,kg$, which is the criterion for this scoring value. The score for the component size is assigned based on the largest component dimension, which is equal to $8\,cm$ for component 11 and equal to $39\,cm$ for component 12 respectively. This leads to different scores for the component size. Further difference is found in the score for the distance to the maintenance access. The distance is calculated between the component center and the nearest corner of the maintenance access. For component 11, this distance is equal to $39.13\,cm$ and it equals $59.87\,cm$ for component 12. Compared to the maximum possible distance, this results in $C_{dist,\,11} = 10$ and $C_{dist,\,12} = 9$ respectively.

The other scores for the occupied volume, working overhead and access size, are defined by the overall system properties. Therefor, they are identical for all components.

The two highest total scores are reached for components 10 and 11, for which $C_{total,\,i}$ equals 74.56% and 75.67% respectively. Based on the checklist scores for the self-developed procedure in table 4.3 it can be observed, that both components have identical scores for the accessibility and the human factor checklist. However, for the geometry checklist there is a difference of 0.33 points between the scores for component 10 and 11. The property scores of the geometry checklist in table C.6 reveal, that the difference results from the score for the distance between connected components. Referring to the component list in table 4.1, it is noticed that both components are only connected to component 9 (reservoir). The distance to the center of the reservoir is $35.50\,cm$ for component 10 and $27.50\,cm$ for component 11 resulting in scores of 9 and 10 respectively, considering a maximum possible connection length of $290\,cm$. For Procedure III, both components have the same accessibility percentage. This highlights, that the self-developed procedure detects more differences between components due to a more immersive maintainability prediction.

Optimization

The system is also optimized with regard to the self-developed procedure. For reasons of comparability, the optimization parameters correspond to those of Procedure III. The allowed movement is set to $\Delta_{allowed} = 20\,cm$ and the maximum function evaluations limit is set to $e_{max} = 200$. The optimized system is shown in figure 4.10b. The overall score C_{total} is equal to 7.34 after the optimization. This corresponds to an improvement of 9.88% compared to the reference system.

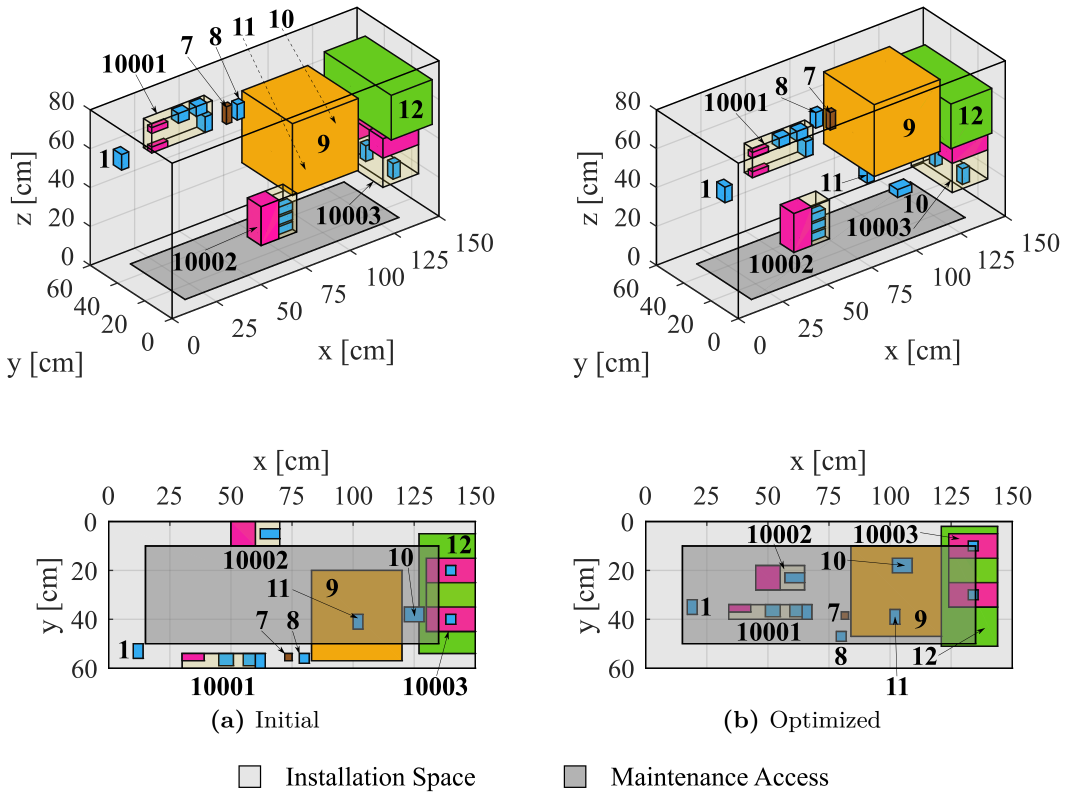


Figure 4.10: Comparison of the initial reference system (a) and the system after optimization (b) with regard to the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Similar to Procedure III, the optimization cannot change every score of the self-developed procedure. Scores that can be ameliorated by the optimization are the scores for occupied volume, distance between connected components, haptic access, visual access, packaging, space around the component as well as the distance between the component and the maintenance access. Those scores are compared for both, the reference and the optimized system, in figure 4.11. Represented are the total values for the system, which equals the average of the individual component scores, as no component weighting is used.

It can be seen, that the largest improvement is achieved for the visual access score, which improved from 4.1 to 9.2 points. This goes along with the appearance of the system in figure 4.10b, as the components moved towards the maintenance access in x- and y-direction, compared to the initial reference system. All components except component 12 and 10003 are fully visible in the optimized system. Another significant improvement is achieved for the

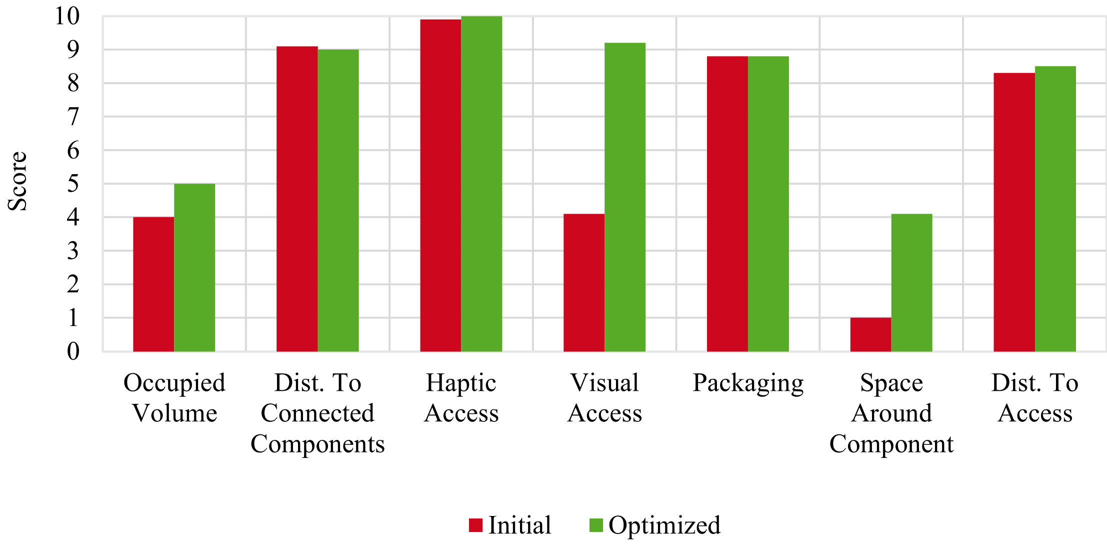


Figure 4.11: Comparison of the scores of the self-developed procedure, which can be changed by the optimization. Optimization performed regarding the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

space around the component score. For the reference system, this score is equal to 1, as no component has at least $6\,cm$ of free space around it. After optimization, this score grew to 4.1 and just components 10003, 7, 8, 9 and 12 still have the lowest score of 1. The other components now have a score of 6, which corresponds to at least $10\,cm$ of free space, or a score of 8, equaling at least $13\,cm$ of space around the component.

The score for the occupied volume is also increased by 1, compared to the reference system. In the initial reference system, the occupied volume is equal to 61.83% of the total volume of the installation space. This is reduced to 57.04% for the optimized system, resulting in the augmented score C_{vol}. The haptic access score is increased by 0.1 and is equal to 10 for the optimized system, as every component is haptically accessible from at least five sides by only considering the installation space and no other components. In the reference system, component 12 is accessible from only four sides.

The score for the distance between the component and the maintenance access is augmented by 0.2 points compared to the reference system. This is due to the fact, that the score $C_{dist,\,i}$ is augmented from 8 to 9 for components 10002 and 1.

The score for the distance between connected components is decreased by 0.1 points compared to the reference system. The difference results from the $C_{ConLength,\,i}$ score of component 11, which is equal to 9 for the optimized system and equal to 10 for the initial reference system. The reduced score can be justified with the value of $l_{total,\,i}$ for component 11, which is increased by $19\,cm$ compared to the reference system.

The packaging score remains constant compared to the reference system, although $C_{pack,\,i}$ is different for two components. Component 10003 requires the removal of one component in the optimized system, compared to two in the initial reference system. Therefor, $C_{pack,\,10003}$ is augmented by 1 for component 10003. Contrary, component 9 requires the removal of two components, instead of one as in the reference system, resulting in $C_{pack,\,9}$ reduced by 1. As those values neutralize each other, the overall packaging score is equal for the optimized and the initial reference system.

Checklist Weighting

Two different weighting mechanisms are included in the self-developed procedure. At first, the weighting of the checklist scores is considered. This allows to give each of the three checklists a different influence on the total score. Different combinations of weighting factors W_{geo}, W_{acc} and W_{HF} are applied to the reference system. The resulting total scores can be seen in table 4.4.

Case	C_{geo}	C_{acc}	C_{HF}	W_{geo}	W_{acc}	W_{HF}	C_{total}
Ref	7.63	6.26	6.13	1	1	1	6.68
1	7.63	6.26	6.13	10	1	1	7.39
2	7.63	6.26	6.13	1	10	1	6.44
3	7.63	6.26	6.13	1	1	10	6.37
4	7.63	6.26	6.13	10	10	1	6.91
5	7.63	6.26	6.13	10	1	10	6.85
6	7.63	6.26	6.13	1	10	10	6.27

Table 4.4: Checklist and total scores of the self-developed procedure applied to the reference system with different checklist weighting factors.

As the geometry score has the highest value of all three scores, it is obvious, that the total score is increased when the geometry checklist has a higher weighting factor than one or both of the other checklists. The actual benefit of the weighting is found in the optimization.
An optimization is performed for case 6, as the considered weighting puts emphasis on the two lowest checklist scores, C_{acc} and C_{HF}. The optimization parameters are again set to $\Delta_{allowed} = 20\,cm$ and $e_{max} = 200$. The weighted total score after optimization equals 7.08 which corresponds to an improvement of 12.92% compared to the initial overall score for case 6. The score for accessibility checklist is significantly augmented by 1.66 points to $C_{acc} = 7.92$. The human factor checklist score is increased by 0.05 points, resulting in $C_{HF} = 6.18$. On the other hand, the geometry score is decreased by 0.06 points. This is expected, as the geometry checklist is less weighted than the other two.

The influence of the optimization on the changeable system properties is shown in figure 4.12. For the geometry checklist, the scores for the occupied volume and the distance to connected components can be changed by the optimization. Compared to the reference system, the occupied volume score remained constant. The score for the distance to connected components is decreased by 0.2 points.
It can also be seen, that the largest improvements are achieved for the visual access and the space around the components, which are two of the four changeable scores of the accessibility checklist. The haptic access score is improved to the optimal value of 10. The packaging score is decreased by 0.1 points. To access component 9, four other components must be removed,

thus $C_{pack,\,i}$ is equal to 6 for component 9. As mentioned before, the packaging score for component 12 is equal to 1 due to the special case for components that have to be turned before removal. All remaining components do not require the removal of other components and have therefor a packaging score of 10 in the optimized system.

The relatively small improvement of C_{HF} by 0.05 points can be explained by the fact, that only one of the six properties considered in the human factor checklist can be improved by the optimization. The other five all depend on static attributes, as the component size and mass or the maintenance access size and position. Improvable is just the score for the distance between the component and the maintenance access, which is improved from 8.3 to 8.6.

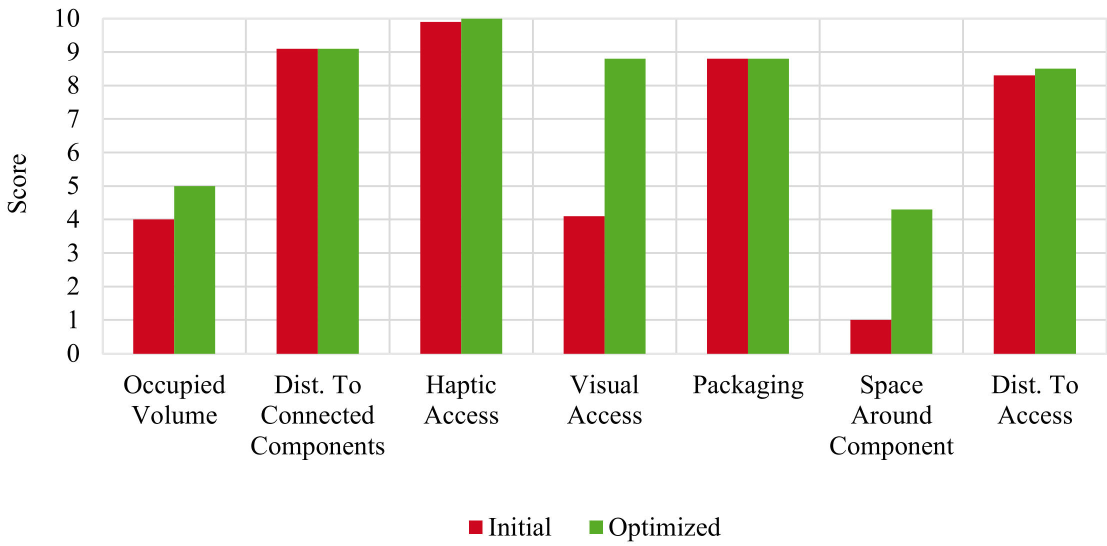


Figure 4.12: Comparison of the scores of the self-developed procedure, which can be changed by the optimization. Optimization performed with regard to the self-developed procedure. $W_{geo} = 1$, $W_{acc} = 10$ and $W_{HF} = 10$, no component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Another optimization is performed for case 1, whereby the score of the geometry checklist is weighted with factor 10 while the accessibility and human factor weighting factors are equal to 1. The weighted overall score is equal to 8.15, which is an improvement of 10.28% compared to the initial score of 7.39 for case 1. The score of the geometry checklist is thereby improved by 0.77 points to a value of 8.4. The score concerning the accessibility checklist, is also improved from 6.26 to 7.72. The score for the human factor checklist remained constant, compared to the reference system. The comparison of the individual scores is illustrated in figure 4.13.

When analyzing this figure, it can be observed that the score for the occupied volume is improved to 6. Compared to the results of the optimization without weighting in figure 4.11, this equals a further enhancement of 1 point. This highlights the benefit of the higher weighting of the geometry checklist, as the second geometry property, the distance between connected components, is also ameliorated. It is further noticed, that the other scores are either increased or remained constant.

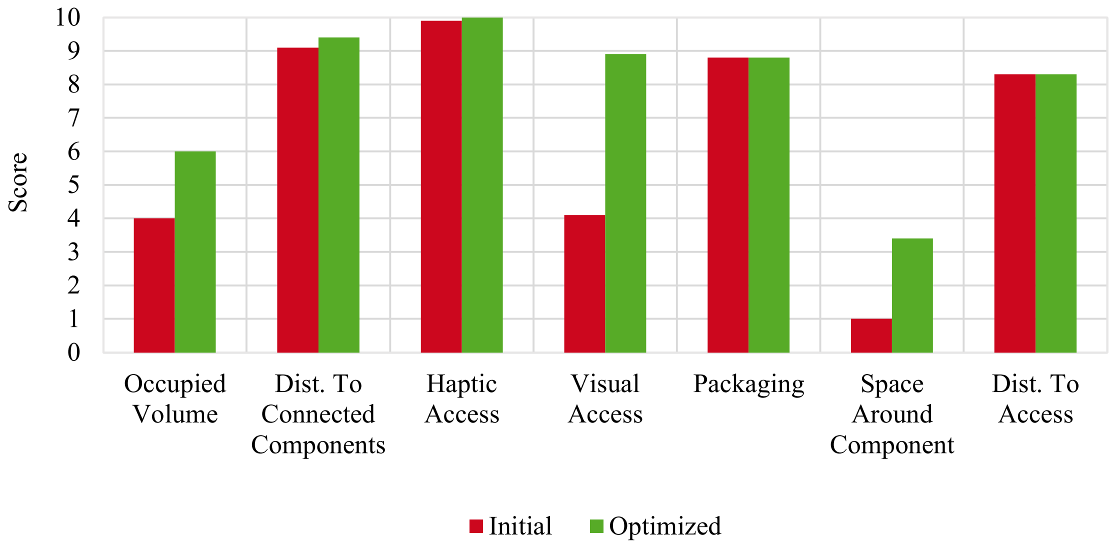


Figure 4.13: Comparison of the scores of the self-developed procedure, which can be changed by the optimization. Optimization performed with regard to the self-developed procedure. $W_{geo} = 10$, $W_{acc} = 1$ and $W_{HF} = 1$, no component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

From the analysis of those results follows, that the checklist weighting is suited to specifically target the amelioration of certain system properties.

Component Weighting

A weighting of the individual components based on their failure rate is also incorporated in the self-developed procedure. The thereby used calculations are presented in chapter 3.4. For the reference system, the failure rates are defined per 10^6 flight hours (FH). The values of the failure rate λ and the associated weighting factors W_i are presented in table 4.5.

Nr.	λ $[10^{-6}\,1/FH]$	W_i
10001	1.21	1
10002	31.56	3
10003	31.56	3
1	31.66	3
7	31.66	3
8	7.79	1
9	62.27	6
10	29.24	3
11	29.24	3
12	121.44	12

Table 4.5: Failure rates λ and associated weighting factors W_i for the components of the reference system.

Using the component weighting, C_{total} is equal to 6.37 for the reference system. This is 4.64% lower compared to the result of the maintainability prediction performed without weighting.

The component with the highest failure rate of 121.44 per 10^6 FH, is component 12. As already mentioned before, this component has also the lowest score $C_{total,i}$ of 5.57, which is 1.11 points below the system average of 6.68. Due to its high failure rate and the associated weighting factor, component 12 alone contributes to 31.58% of the weighted overall score. This explains why the overall score is reduced compared to the assessment without weighting.

Again, the weighting can also be used in combination with an optimization. This aims at specifically augmenting the maintainability of components with higher failure rates as they require replacement more often than other components. The weighted overall score after optimization is equal to 7.04, which corresponds to an improvement of 10.52% compared to the component weighted score of the initial reference system, which is equal to 6.37. The system after the optimization with component weighting is illustrated in figure 4.14b.

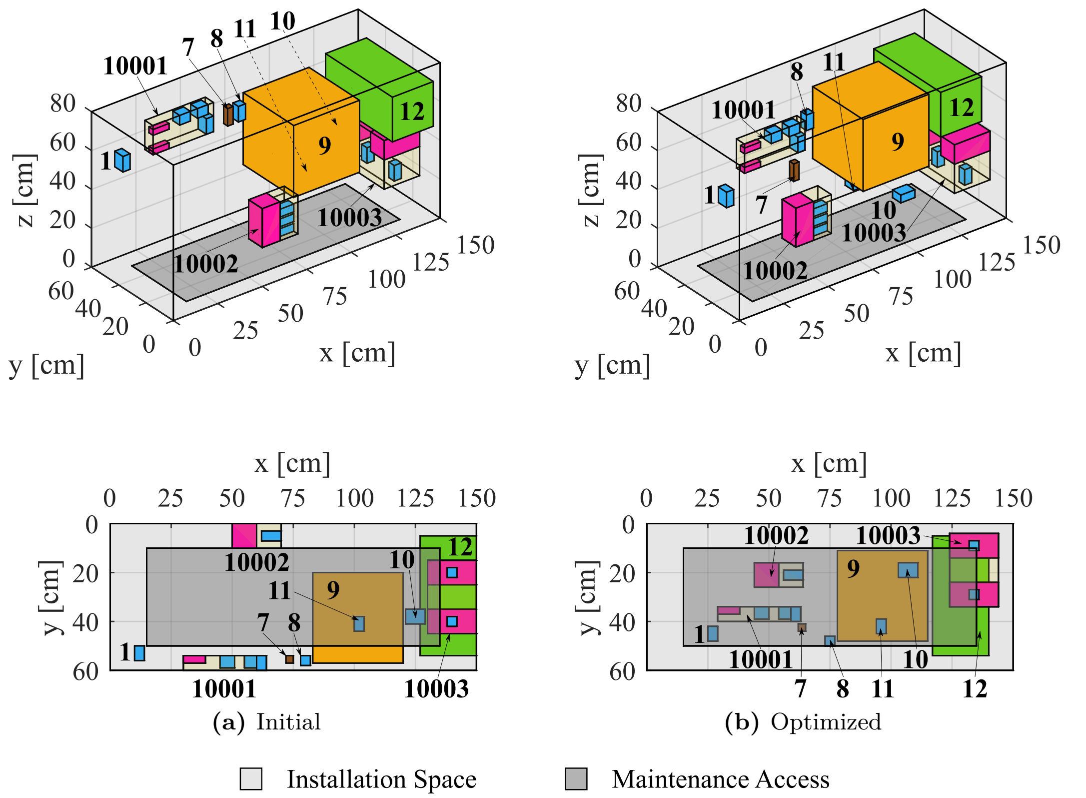


Figure 4.14: Comparison of the initial reference system (a) and the system after optimization (b) with regard to the self-developed procedure with component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

For component 12, the comparison of the scores for the initial reference system as well as for the systems optimized with and without component weighting is shown in figure 4.15. Depicted are the scores that are influenced by the optimization.

It can be seen, that compared to the optimization without component weighting, additional improvement is achieved for the scores concerning the occupied volume and the visual access.

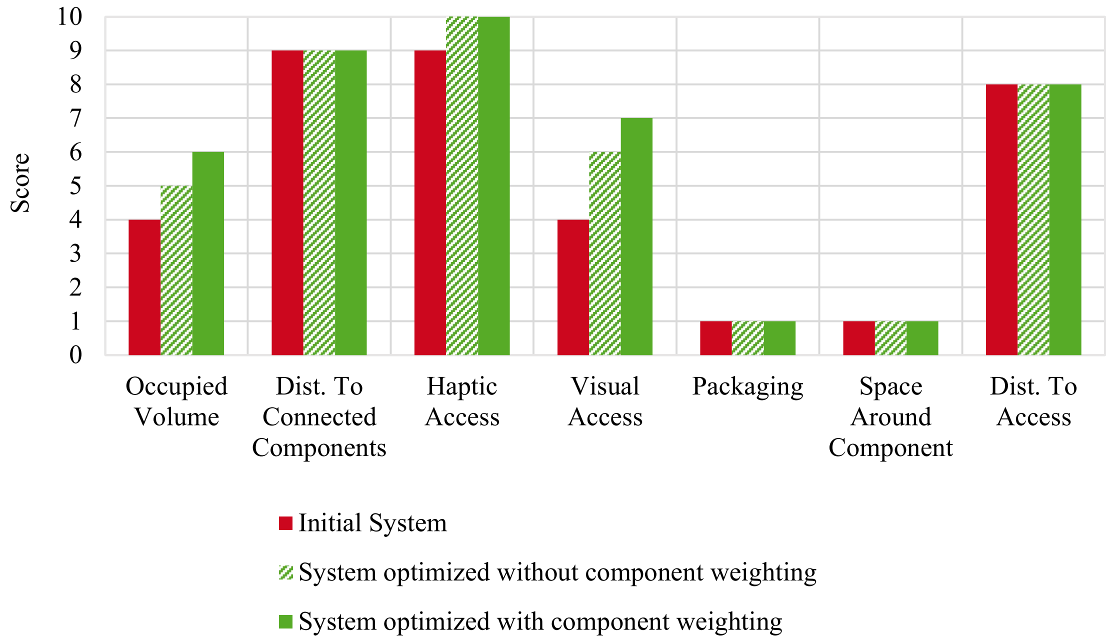


Figure 4.15: Comparison of the scores of the self-developed procedure, which can be changed by the optimization. Scores for component 12 (ACMP). Optimization performed with and without component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

The other scores remained constant, compared to the not-weighted optimization. The packaging score cannot be improved by the optimization, as it results from the fact that component 12 does not fit through the maintenance access without being turned or tilted. The space around the component is also not improvable, due to the y-wise dimension of component 12, which is equal to $49\,cm$. The y-dimension of the installation space equals $60\,cm$. Therefor, even if component 12 would be placed centered and without other components nearby, the available space cannot be larger than $5.5\,cm$ which is below the limit for a larger space around the component score.

For a better comparability, the system that resulted from the component-weighted optimization, shown in figure 4.14b, is also scored by using the self-developed procedure without any weighting mechanism. The resulting total score is then equal to 7.47. Compared to the system in figure 4.10b, which resulted from the optimization without weighting, this corresponds to an improvement of 1.77%. Compared to the total score of the initial reference system, the score is improved by 11.83%.

Optimization Parameters

As mentioned before, the presented optimizations are all performed with $\Delta_{allowed} = 20\,cm$ and $e_{max} = 200$. This is chosen in order to be able to compare the optimization results to those of Procedure III. However, further optimizations are performed for the self-developed procedure considering different values for $\Delta_{allowed}$ and e_{max}.

First, the optimization success compared to the reference system is displayed as a function of $\Delta_{allowed}$ in figure 4.16. The optimizations are performed with $e_{max} = 200$. It can be seen, that the optimization success is not necessarily increased with increasing $\Delta_{allowed}$. This is due to a downside of the used optimization scheme, that was detected when performing the optimizations.

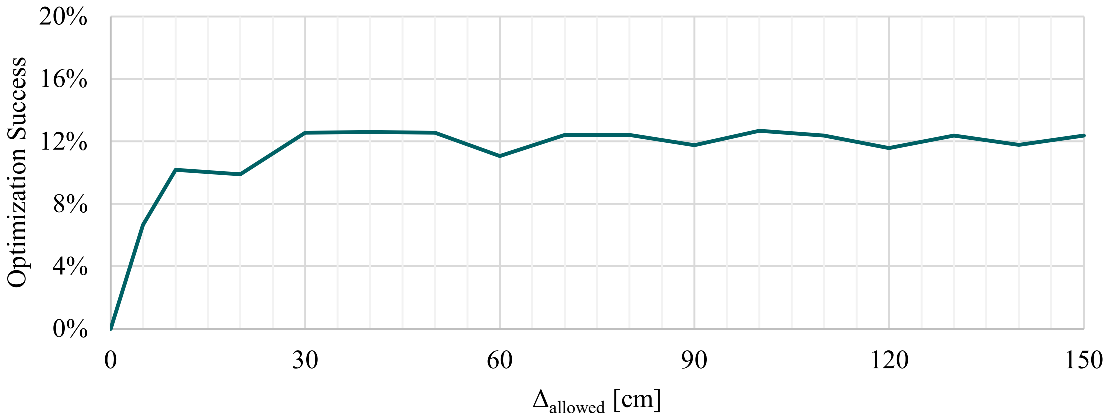


Figure 4.16: Optimization success compared to the reference system as a function of $\Delta_{allowed}$. Optimization performed with regard to the self-developed procedure without weighting and $e_{max} = 200$.

In the optimization, the component positions are optimized for each component individually, one after another in the same order as they reside in the variable '*system*'. Although, the optimizer still determines the optimum function value for the first component, the associated component position can be different, while still resulting in the same score. The new position of the first component however defines the available positions of the following ones, as components cannot be placed within each other. This can either lead to a larger possible optimization success for the following components or to a lower one. To overcome this downside, a simultaneous optimization of all components is suggested as a future development of this tool.
Further, it must be noted, that the surrogate optimization starts with random trial points. This intensifies the aforementioned problem as the optimizer never trials the same component positions, when being performed multiple times with the same system and the same optimization settings. Beside those downsides, it can be deducted from figure 4.16, that no significant improvement of the optimization success is achieved above $\Delta_{allowed} = 30\,cm$.

Augmenting the function evaluations limit e_{max} also has an influence on the achieved optimization success. A higher value means that a larger variety of component positions is trialed. Therefor, the chance of finding the actual optimum value of the objective function for the considered component is augmented. However, as before, the new position of the component affects the optimization of the following ones.
The effect of the maximum functions evaluations limit on the optimization success with regard to the self-developed procedure is shown in figure 4.17. The allowed movement is set to $150\,cm$ which is equal to the largest installation space dimension. Again, no strict depen-

dency between the optimization success and e_{max} can be detected, which is caused by the aforementioned downsides of the optimization scheme. However, it can also be seen that the optimization success does not significantly grow for values above $e_{max} = 200$.

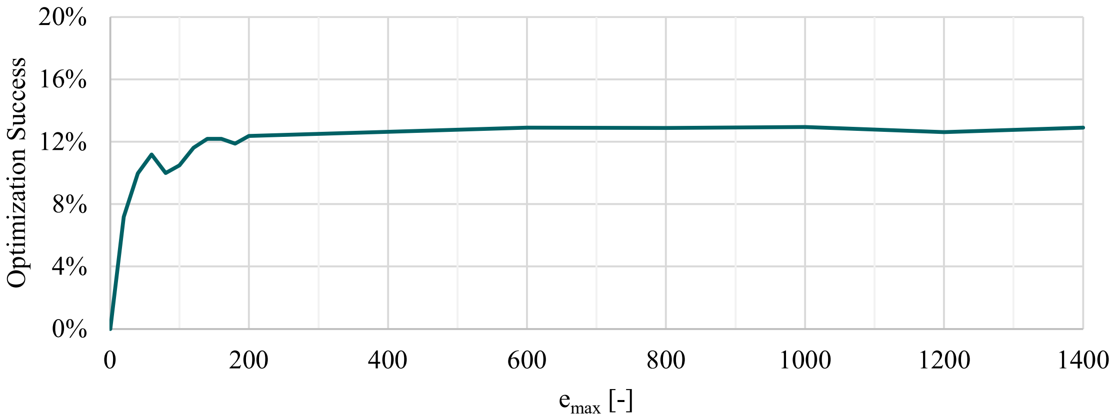


Figure 4.17: Optimization success compared to the reference system as a function of e_{max}. Optimization performed with regard to the self-developed procedure without weighting and $\Delta_{allowed} = 150\,cm$.

4.1.3 Comparison of the Procedures

To further validate the results of the self-developed procedure, a comparison to the results of the established Procedure III is performed. To enhance the comparability to the accessibility percentage of Procedure III, the values for C_{total} and $C_{total,\,i}$ are multiplied by 10 to obtain the accessibility percentage of the self-developed procedure. A comparison between the accessibility percentages of both procedures is given in table 4.6. The values are based on the evaluation of the initial reference system and without using the checklist weighting or the component weighting.

It can be seen, that the difference between the highest and lowest scores is 50 percentage points for Procedure III, compared to just 20 percentage points for the self-developed procedure. This can be reasoned by the fact that the self-developed procedure evaluates the maintainability more precisely due to the larger scoring range. As an example, the internal access to the component is scored between 0, 2 and 4 in Procedure III, whereby the score is defined by the possibility to gain haptic and/or visual access to the component. In the self-developed procedure, the visual and haptic access are scored separately based on the visible percentage of the component surface and based on the reachable component sides. The visual access score is different for partially and fully visible components, which is not the case in Procedure III. For visual inspections however, it is very well a difference if the component is completely visible or not.

Nr.	Accessibilty Percentage Procedure III	Accessibility Percentage Self-developed Procedure
10001	80.77	66.11
10002	80.77	63.89
10003	48.08	62.67
1	80.77	68.00
7	80.77	69.11
8	80.77	69.11
9	61.54	62.78
10	84.62	74.56
11	84.62	75.67
12	34.62	55.67

Table 4.6: Comparison of the accessibility percentage values of Procedure III and of the self-developed maintainability prediction for the reference system.

Another difference is found in the packaging score. For both procedures, the components that have to be removed are determined using the same process. But for Procedure III, the evaluation only differentiates if none, one or more than one components have to be removed, resulting in scores of 4, 2 or 0. On the other hand, the self-developed procedure allows ten different packaging scores. For example, two other components have to be removed in the reference system to gain access to component 10003. For Procedure III, this would result in the lowest possible score of 0. The self-developed procedure evaluates this packaging with a score of 8, which is nearer to the highest than to the lowest possible score.

Overall, the lowest accessibility percentage is achieved for both procedures for component 12 and the highest one for component 11. For Procedure III, the highest accessibility percentage of 84.62% is additionally achieved for component 10. This component has only the second highest accessibility percentage for the self-developed procedure. This again reinforces, that the self-developed procedure allows a more diversified scoring of the component and system properties.

To further verify that the results of the self-developed procedure are reliable, the accessibility percentage values of table 4.6 are graphically illustrated in the following figure 4.18. From this it can be seen, that the self-developed procedure not only predicts the highest and lowest accessibility percentage for the same components as Procedure III, but both also have similar curve progressions.
The graph for the self-developed procedure has thereby less steep gradients compared to the graph for Procedure III. This goes along with the already mentioned observation that the self-developed procedure has a smaller difference between highest and lowest accessibility percentage.

The optimization with regard to Procedure III leads to an improvement of the accessibility percentage by 9.93%. The success of the optimization with regard to the self-developed procedure is equal to 9.88%. This value is lower than the optimization success which is

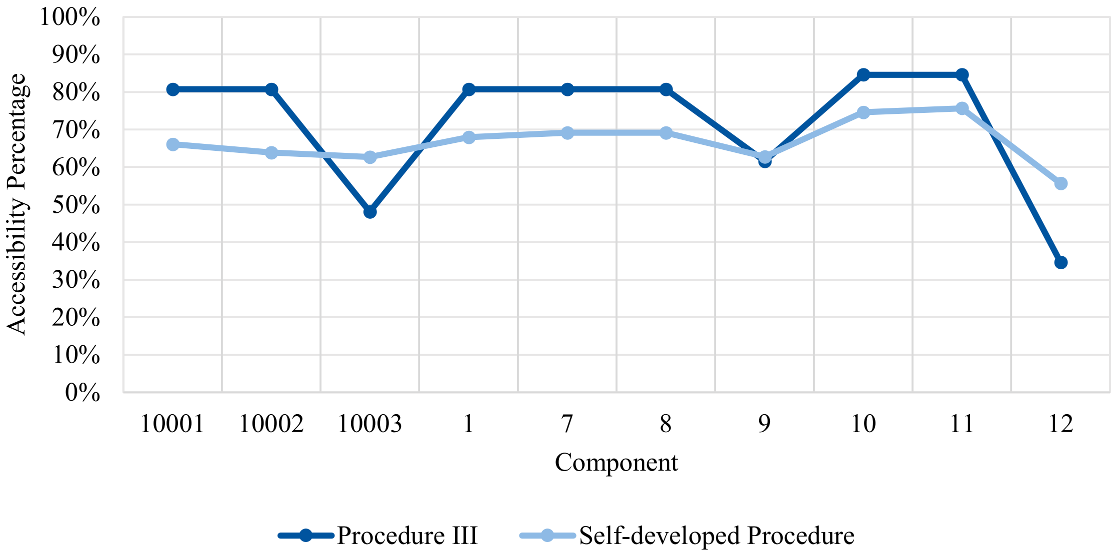


Figure 4.18: Comparison of the accessibility percentage of Procedure III and of the self-developed maintainability prediction for the components of the reference system.

achieved by optimizing the reference system regarding Procedure III. Both optimizations are performed with $\Delta_{allowed} = 20\,cm$ and $e_{max} = 200$. However, as explained in chapter 4.1.1, that with regard to Procedure III, this corresponds to the highest achievable optimization success as all improvements that are feasible for the reference system have been attained.

In contrast to this, a larger optimization success can be achieved with regard to the self-developed procedure when using different optimization settings or the weighting mechanisms. For the optimizations performed within this thesis, the largest improvement of 12.94%, compared to the reference system, is achieved for an optimization with $\Delta_{allowed} = 150\,cm$ and $e_{max} = 1000$, without the use of any weighting mechanism. This is larger than the optimization success with regard to Procedure III. However, it is noted that it is possible, that other combinations of optimization settings and weightings can lead to a further increased optimization success regarding the self-developed procedure. It cannot be determined, which accessibility percentage is the largest achievable one for the self-developed procedure. This is due to the fact that trade-offs between different system properties are included in the self-developed procedure. For instance, the targeted augmentation of the space around the component stands in conflict with the likewise targeted reduction of the occupied volume and of the distance to connected components.

For the self-developed procedure, seven scores can be changed by the optimization process, compared to just three for Procedure III. In addition to the packaging as well as the haptic and visual access, which are also considered in Procedure III, the self-developed procedure allows the optimization of the occupied volume, the distance to connected components, the space around the component and the distance between the component and the maintenance access. Due to the larger scoring range of the self-developed procedure, even small improvements can have an influence on the overall score.

Overall it can be conducted, that the self-developed procedure predicts the maintainability equally reliable as Procedure III. The advantage of the self-developed procedure is a more accurate scoring, due to the detailed scoring range and due to taking into account more system properties. The evaluations of the self-developed procedure are all dependent on system properties known during the preliminary design stage and they do not require assumptions. In contrast to this, the questions C3, 4 ,5 , 6, 8, 9 and 10 of Procedure III can only be scored automatically after defining the amount of steps for the removal of the components. When using the maintainability prediction during the preliminary design stage, the detailed mounting of the components is not yet known and therefor the steps for removal cannot be specified precisely.

In contrast to the self-developed procedure, the Procedure III allows to predict the mean corrective maintenance time. But those values should be regarded with caution when using the simple approach. As mentioned in chapter 4.1.1, the complete approach leads to more accurate MCT values but it can only be applied when the required information is provided for the considered system.

4.2 Condensed System

As the space in aircrafts is limited, a modification of the reference system is also considered. The system is thereby a condensed version of the initial reference system. Therefor, the components are moved closer together. The x-dimension of the installation space is reduced from $150\,cm$ to $100\,cm$ and the z-dimension is reduced from $80\,cm$ to $60\,cm$. The y-dimension of the installation space remains constant and has a value of $60\,cm$. The size of the maintenance access is also adjusted, having a x-dimension of $70\,cm$ instead of the previous $120\,cm$, while its y-dimension remained constant. The modified system is displayed in figure 4.19, as a 3D-illustration and as a projection in the x-y-plane, viewed from $z = 0$. The associated new component positions are presented in table C.20. As for the reference system, the maintainability is scored and optimized regarding Procedure III and the self-developed procedure.

4.2.1 MIL-HDBK-472 Procedure III

Maintainability Prediction

Procedure III is performed using the same settings as for the reference system. This means, that the summarized scores for the simple approach are set to $C_{A,\,simple} = 39$, $C_{B,\,simple} = 15$ and $C_{C,\,simple} = 3$. Furthermore, the steps of removal are equal to $s_i = 4$ for each component. The overall accessibility percentage of Procedure III is equal to 69.42%, when being applied to the condensed system. Compared to the reference system, whose accessibility percentage

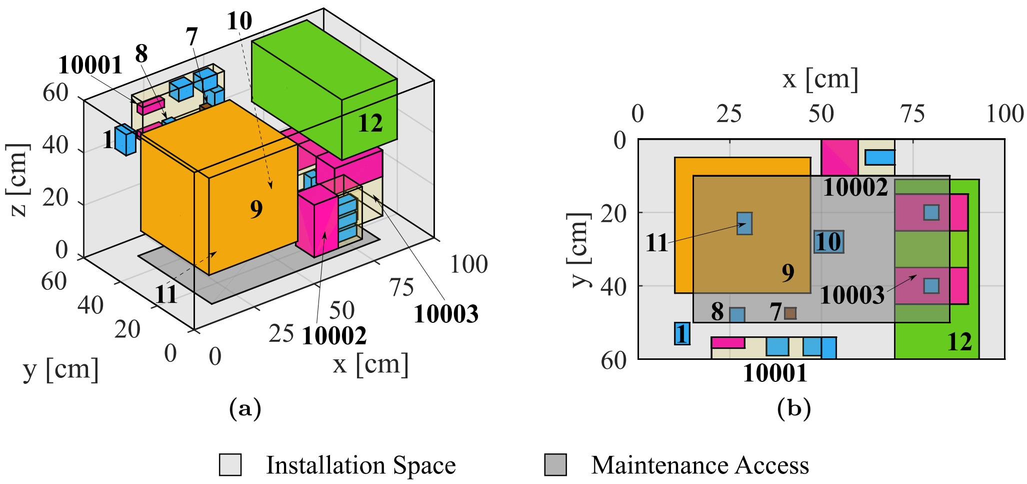


Figure 4.19: Condensed system, shown as a 3D-illustration (a) and as a projection in the x-y-plane, viewed from $z = 0$ (b).

is 71.73%, this corresponds to a deterioration of 3.22%. The individual accessibility scores for the components of the condensed system are listed in table 4.7. The scores for the initial reference system are shown in table 4.2.

Nr.	C_{A4}	C_{A5}	C_{B3}	C_{B6}	C_{C1}	C_{C2}	C_{steps}	Accessibilty Percentage
10001	2	0	4	4	3	4	1	46.15
10002	2	4	4	4	3	4	3	80.77
10003	4	4	4	4	3	3	3	82.69
1	2	4	4	4	3	4	3	80.77
7	4	4	4	4	3	4	3	84.62
8	4	4	4	4	3	4	3	84.62
9	4	0	4	4	3	1	0	30.77
10	4	4	4	4	3	4	3	84.62
11	4	4	4	4	3	4	3	84.62
12	4	0	4	4	3	3	0	34.62

Table 4.7: Automatically evaluated accessibility scores for the condensed system.

As for the reference system, the highest accessibility percentage of 84.62% is reached for components 10 and 11. Additionally, components have also an accessibility percentage of 84.62% in the condensed system. The lowest accessibility percentage is different for both systems. For the reference system it is equal to 34.62% for component 12. This component still has the same accessibility percentage in the condensed system, but it is undercut by component 9, which has an accessibility percentage of 30.77%. Other significant differences can be observed for components 10001 and 10003. For the first, the accessibility percentage was reduced by 34.62 percentage points and for the second, it is augmented by 34.61 percentage points. Some scores are not affected by the modified system architecture and are therefor identical for both systems. This accounts for the scores C_{B3}, C_{B6}, C_{C1} and C_{C2}.

The position-dependent scores for both systems are displayed in figure 4.20, to illustrate the differences between the scores of the condensed system and of the reference system.

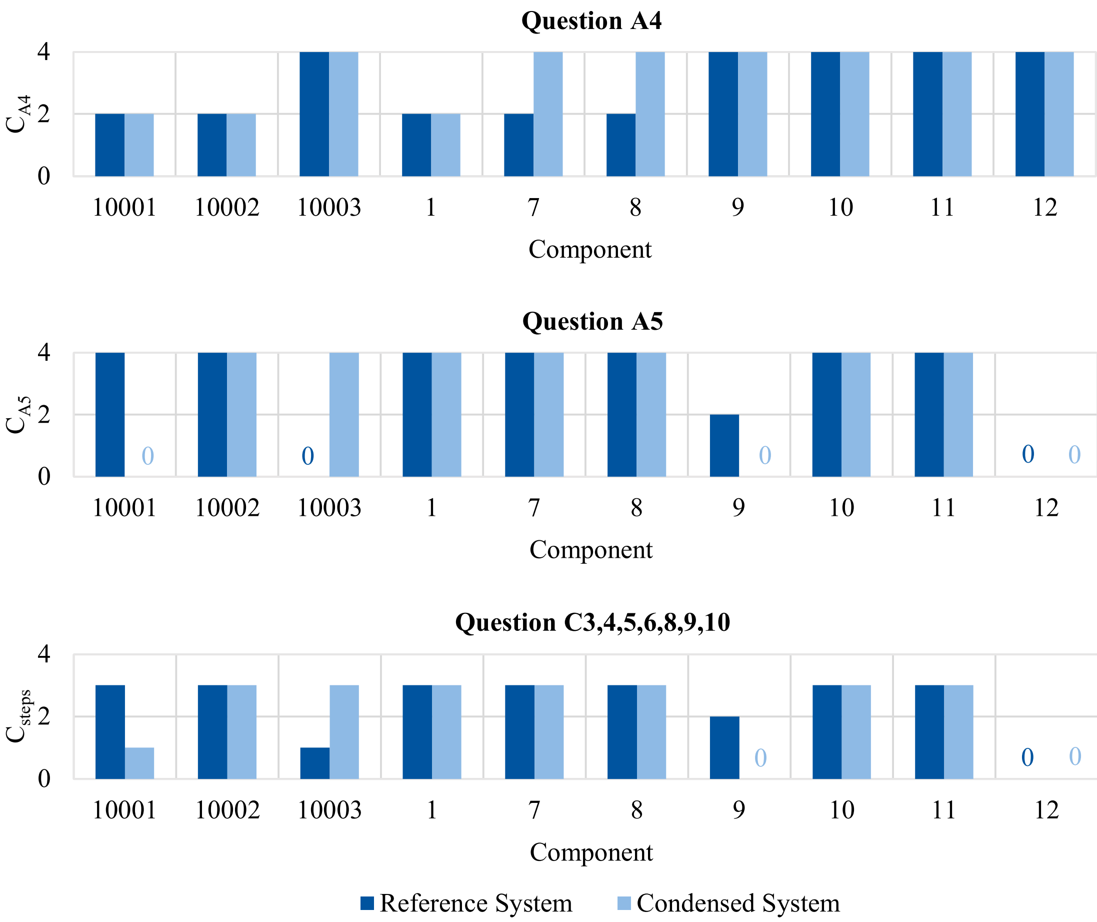


Figure 4.20: Comparison of the scores C_{A4}, C_{A5} and C_{steps} for the reference system (dark blue) and the condensed system (light blue).

When considering the internal access score C_{A4}, it can be seen that it is improved, compared to the reference system, for components 7 and 8. Those components are placed outside of the maintenance access in the reference system and are therefor not visible. In the condensed system however, they are placed completely within the maintenance access, which explains the augmented values for C_{A4}.

Further differences are observed in the packaging scores for the components 10001, 10003 and 9. While component 10001 cannot be removed without removing at least two other components, component 10003 experienced an opposite change. It can be removed without removing any other component of the condensed system. Component 9, which only requires the removal of one other component in the reference system, requires the removal of 5 components in the condensed system. Therefor its packaging score is reduced from 2 to 0. The step-dependent scores C_{steps} follow again the same trends as the packaging scores C_{A5}, as the need to remove more components also results in more maintenance steps.

Optimization

The limitations of the condensed system become more clear when performing an optimization. The optimization parameters are set to $\Delta_{allowed} = 20, cm$ and $e_{max} = 200$. The optimization of the condensed system regarding Procedure III results in an overall accessibility percentage of 74.04%, which corresponds to an improvement of 6.66%. The optimized version of the condensed system is shown in figure 4.21b.

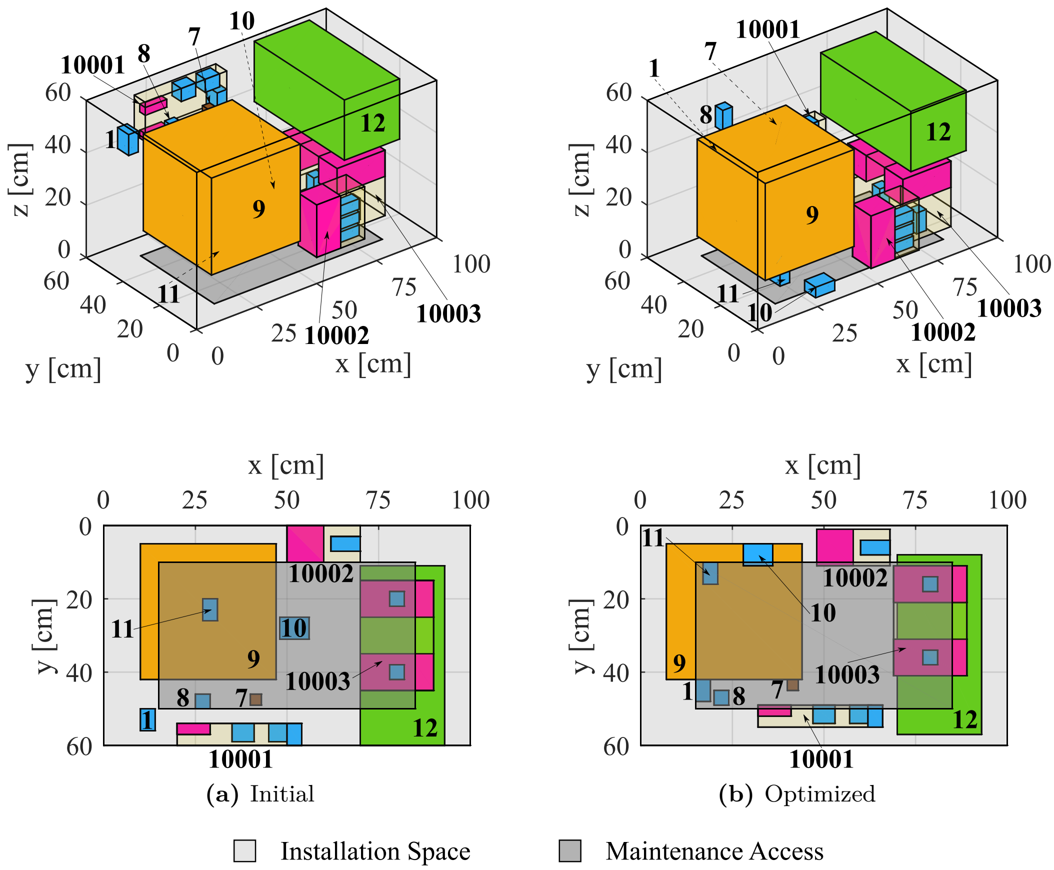


Figure 4.21: Comparison of the initial condensed system (a) and the condensed system after optimization (b) with regard to Procedure III. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

The limited optimization success can be reasoned with the restricted installation space and the therefore more limited moving possibilities, compared to the reference system.
The scores that can be changed by the optimization are shown in figure 4.22 for the condensed system and the optimized version of it.

For question A4 (internal access), every component has the optimal score of 4. This can be explained with respect to the 2D-illustration of the optimized system in figure 4.21b. There, it can be seen that every component is at least partially placed within the maintenance access.

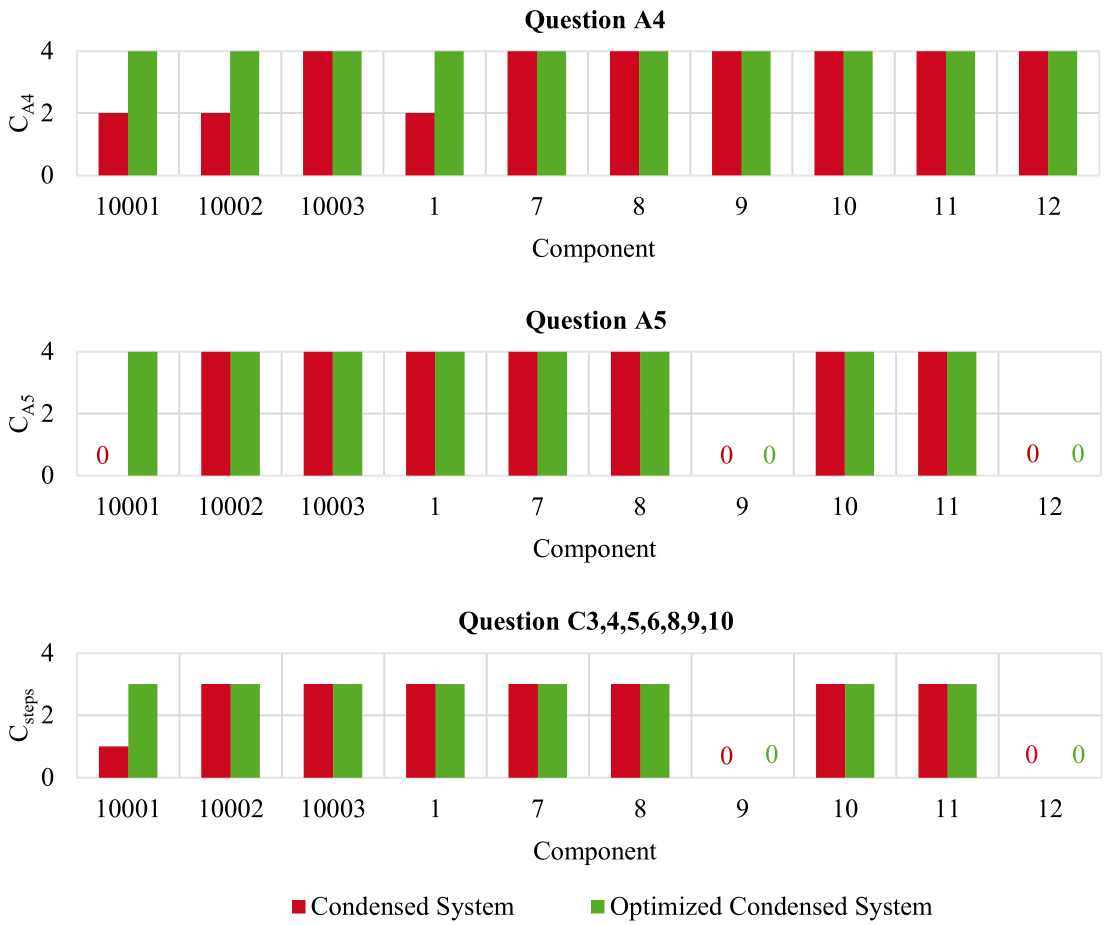


Figure 4.22: Comparison of the scores C_{A4}, C_{A5} and C_{steps} of Procedure III for the initial condensed system and the optimized version of it. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Haptic access is given for all components before and after the optimization.
The packaging is also ameliorated for component 10001, which can be removed without having to remove other components. In figure 4.21b it looks like, component 7 is blocking the removal of component 10001, but this is not the case as component 7 is placed in a higher z-position than component 10001. Therefor it is not between component 10001 and the maintenance access. The score C_{steps} is also improved for component 10001, as no additional steps for the removal of other components are required.

4.2.2 Self-Developed Procedure

Maintainability Prediction

The maintainability of the condensed system is also assessed using the self-developed maintainability prediction. Thereby, neither the checklist weighting, nor the component weighting is used. The total score for the condensed system is equal to 6.67. This is 0.01 points lower compared to the score of the reference system, which is equal to 6.68. The comparison of the individual scores of both systems is illustrated in figure 4.23. The presented scores are the mean values of the component-dependent values, as no weighting was used.

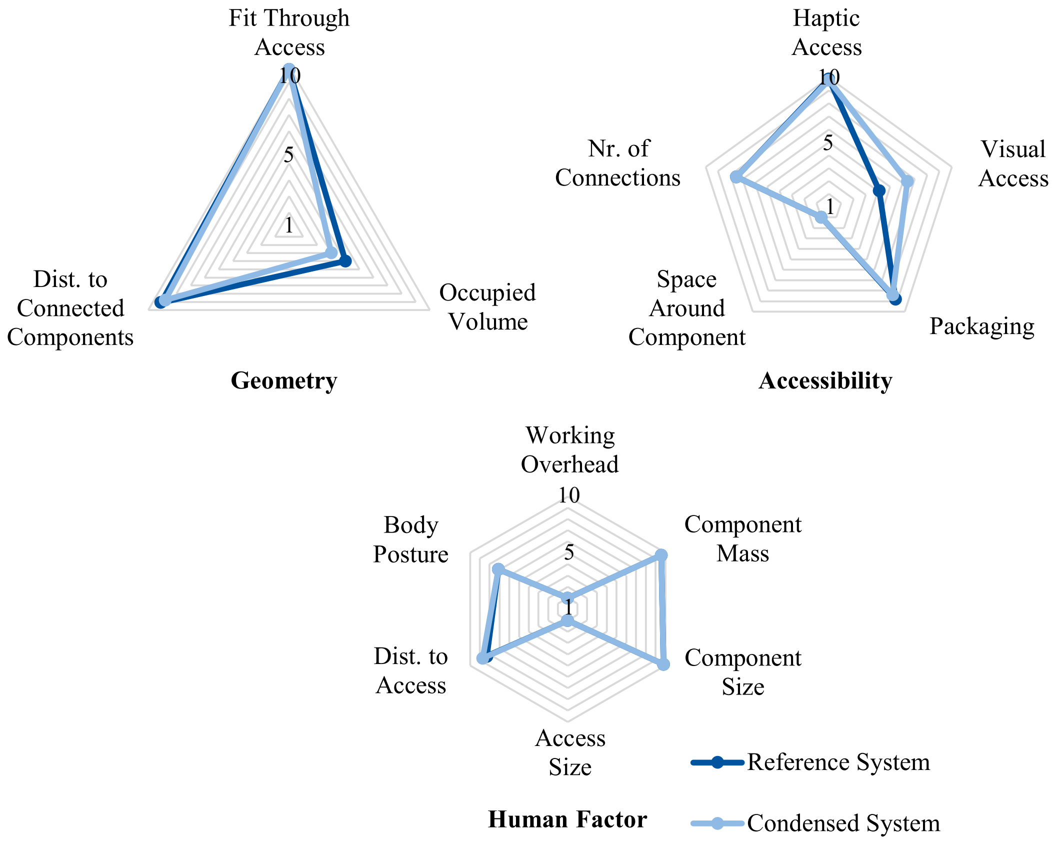


Figure 4.23: Comparison of the scores of the self-developed maintainability prediction for the reference system (dark blue) and the condensed system (light blue).

The occupied volume score is lower for the condensed system than it is for the reference system. Equally, the score for the distance between connected components is reduced by 0.3 points, although the components are closer together due to the condensed system architecture. As it is explained in chapter 3.4.1, this score depends on the percentage of the calculated connection length compared to the maximum connection length. The later is dependent on the installation space dimensions and is therefor smaller for the condensed system than it is for the reference system. This results in higher values for the scoring factor $S_{ConLength,\,i}$ and vice-versa in a lower score $C_{ConLength,\,i}$.

For the accessibility checklist, the visual access score is significantly improved compared to the reference system. This meets the expectations as components 7 and 8 are fully visible and the components 10003 and 12 have a larger visible surface compared to the reference system. The packaging score is decreased, as the access to components 9 and 10001 requires the removal of more components than it is the case in the reference system.

Most of the scores of the human factor checklist depend on the component mass or size and on installation space properties that have not been changed. Therefor, all scores of the

human factor checklist, except the score concerning the distance to the maintenance access, are identical for the condensed and the reference system.
The score for the maintenance access size is defined by the smallest of the two dimensions of the maintenance access. The smallest maintenance access dimension is equal to $40\,cm$ for both, the condensed and the reference system. Therefor, $C_{AccSize}$ is equal to 1 for both systems.
What did change is the score for the distance to the maintenance access, which has a higher value compared to the reference system. This can be explained by the reduced dimensions of the installation space and the more compact system architecture.

Optimization

The condensed system is optimized with regard to the self-developed procedure, resulting in $C_{total} = 7.12$, which equals an amelioration of 6.75%. The optimization is performed with $\Delta_{allowed} = 20\,cm$ and $e_{max} = 200$. The optimization success differs compared to the reference system, even though the condensed and the reference system have similar overall scores before the optimization. With the same optimization settings, C_{total} is augmented by 9.88% for the reference system. The scores of the self-developed procedure, that can be changed by the optimization, are compared in figure 4.24 for the initial and the optimized condensed system.

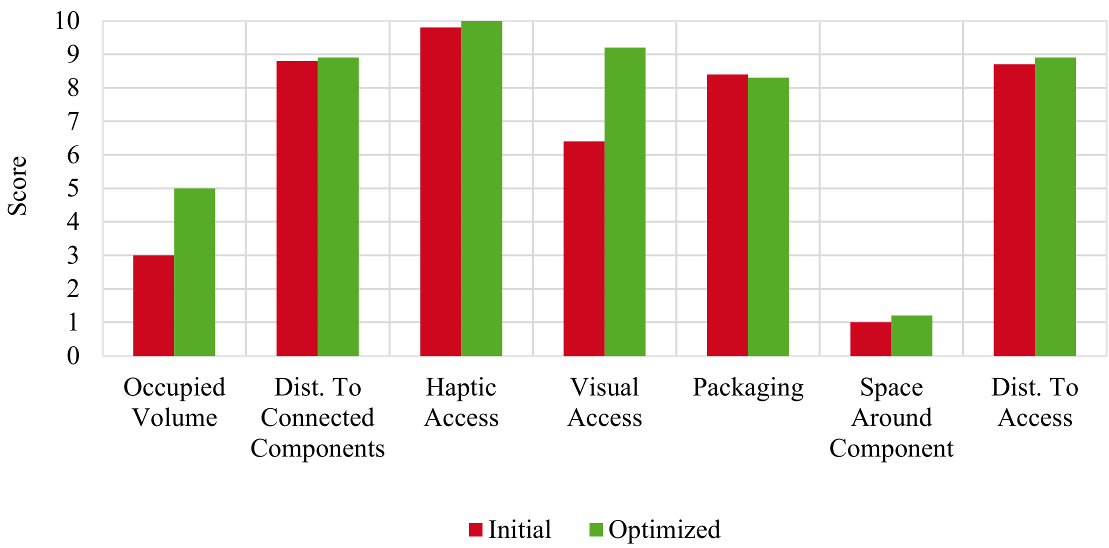


Figure 4.24: Comparison of the scores of the self-developed procedure, which can be changed by the optimization. Optimization applied to the condensed system regarding the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

It can be seen, that all scores but the packaging score are augmented by the optimization. The largest improvement of 2.8 points is achieved for the visual access score. The occupied volume score is augmented by 2 points and the score for the distance between connected components is augmented by 0.1 points. The remaining scores, besides the packaging score, are augmented by 0.2 points. The optimization of the reference system resulted, as it can be seen in figure 4.11 in an augmentation of the space around the component score by 3.1 points. Compared to the improvement of just 0.2 points for the condensed system, this highlights the limitations due to the restricted installation space in the condensed system.

In this chapter, the results for both procedures were discussed. For this, they were applied to the reference system and to a condensed version of it. It can be seen that both procedures produce satisfactory results and that both follow the same patterns. The optimization success is in the same range for both procedures, but it can be further augmented regarding the self-developed procedure when using different optimization settings or the weighting mechanisms. For both procedures, the optimization success depends on the allowed movement range. The highest achievable accessibility percentage is achieved with $\Delta_{allowed} = 20\,cm$ for Procedure III. For optimizations with regard to the self-developed procedure, the considered trade-offs between different system properties lead to the fact, that the highest achievable accessibility percentage is not predictable. However, it was detected that for values of $\Delta_{allowed}$ larger than $30\,cm$ no significant improvement is achieved for optimizations regarding the self-developed procedure with $e_{max} = 200$. It should be noted, that those evaluations only account for the here considered reference system.
The maintainability prediction of the condensed system resulted in lower values compared to the reference system. The results of the optimizations applied to the condensed system highlighted the limitations which result from the restricted installation space.

5 Conclusion and Outlook

The aim of this master thesis was to implement a suitable methodology for assessing the accessibility of an aircraft system. The methodology should consider various system characteristics that influence the duration and effort of the maintenance process. These include component size, component mass, tool space, disassembly-assembly sequence and the ergonomic consideration of the maintenance process. The methodology should be designed to be applied during the preliminary design stage.

For this purpose, Procedure III of US Military Handbook 472 was first selected [16]. It is an established methodology for predicting the mean corrective maintenance time. This methodology takes into account multiple system characteristics, but some evaluation criteria do not allow objective evaluation and require the user's interpretation. Furthermore, not all of the 32 considered criteria can be evaluated using the system properties known at the preliminary design stage.

To compensate for the disadvantages of Procedure III, a new methodology was developed as part of this thesis. In addition to the aforementioned required system characteristics, it also takes into account the occupied volume, the distance between connected components, the number of connections, the size of the maintenance opening, the haptic and visual access to the component. The ergonomics are considered including the posture assessment according to the REBA method, the need of working overhead and the distance between components and the access opening. These take into account statistical values for the body dimensions. The considered system characteristics were grouped into three checklists. The methodology also allows weighting factors to be used to assign a higher proportion of the overall result to individual checklists. In addition, the individual components can also be weighted based on their failure rate. Both weighting mechanisms are optional and can be used separately. The self-developed procedure quantitatively assesses the maintainability by using a scoring range between 1 and 10. However, it does not predict maintenance times, as required knowledge about the mounting of the components is not yet known in the preliminary design stage.

A part of the hydraulic system of a Boeing 777 was selected as the reference system. It consists of a total of 20 individual components, whereby some are installed in modules. Both the installation space and the components are represented as cuboids.

For validation, the two procedures were applied to the reference system. Both showed reasonable results. The results of the self-developed methodology thereby also followed the same patterns as those of Procedure III. It could be seen that the more detailed gradation of the scoring range led to a smaller difference between the lowest and highest value of the accessibility percentage of the individual components for the self-developed procedure. The comparison of both methodologies also showed that the self-developed maintainability prediction was able to extract differences for components that received an identical rating using Procedure III. This highlights the more refined evaluation of the self-developed methodology, compared to Procedure III.

In addition, a condensed version of the reference system was also considered. The component arrangement, the dimensions of the installation space and of the maintenance opening were changed. Again, both methodologies showed reasonable results, although the difference to the original reference system initially appeared smaller than expected. On closer inspection, however, it was found that the disadvantages caused by the more compact arrangement were offset by the changed ratios between the components and the installation space. It should also be noted that some of the considered system properties, such as component size and mass, are not dependent on the system architecture. Thus, the associated scores are identical for both systems, limiting the possible difference between the two systems.

The maintainability evaluation was also used to optimize the system layout with regard to increasing maintainability. The components are thereby moved within a defined allowed movement range. At first, optimizations were carried out for the reference system, using both procedures and an allowed movement of $20\,cm$. An increase in the overall score could be achieved for both methodologies. It was noticed, that the largest optimization success was achieved by the optimization with regard to the self-developed procedure. The success of the optimization depends on the selected allowed movement range.
For the self-developed methodology, the use of the two weighting mechanisms has also an influence on the optimization. With the optimization regarding the checklist weighting, a targeted improvement of specific scores was achieved. The optimization taking into account the component-dependent weighting also led to an improvement of $C_{total,\,i}$ for component 12, which has the highest failure rate and therefor also the largest weighting factor W_i.
The condensed system was also optimized using both methodologies. Thereby, the reduced installation space dimensions led to a lower achievable optimization success compared to the reference system.

In general, the here presented implementation of the methodologies, of the system and of the optimization provide a basis for future developments. One topic that should be improved is the packaging evaluation of components that have to be turned to fit through the maintenance access. Another suggested development is to not only move but also turn the components during the optimization and to implement a simultaneous optimization of all components. Moreover, the trade-off between the maintenance access size and its impact on structural properties should be considered in future studies.

Bibliography

[1] Alderighi, M.; Cento, A.; Nijkamp, P.; Rietveld, P.: Competition in the European aviation market: the entry of low-cost airlines. Journal of Transport Geography, Vol. 24, pp. 223–233, 2012.

[2] Andreacchio, M.; Bekrar, A.; Benmansour, R.; Trentesaux, D.: Balancing preventive and corrective maintenance of aircraft assets: A cyber-physical systems approach. In: pp. 500–503.

[3] Assaf, A. G.; Josiassen, A.: European vs. U.S. airlines: Performance comparison in a dynamic market. Tourism Management, Vol. 33, No. 2, pp. 317–326, 2012.

[4] Berlin, C.; Adams, C.: Production Ergonomics: Designing Work Systems to Support Optimal Human Performance, Ubiquity Press, ISBN 9781911529125, 2017.

[5] BGI 582. Sicherheit und Gesundheitsschutz bei Transport- und Lagerarbeiten. BG-Information, 2008.

[6] Bin Wan Husain, W. M. S.: Maintainability Prediction for Aircraft Mechanical Components Utilising Aircraft Feedback Information. Cranfield University, PhD thesis, 2011.

[7] Bin Wan Husain, W. M. S.: Role of Aircraft Feedback Information in Developing Maintainability Allocation Index. International Journal of Materials, Mechanics and Manufacturing, pp. 299–302, 2015.

[8] Bineid, M.: Aircraft Systems Design Methodology and Dispatch Reliability Prediction. Cranfield University, PhD thesis, 2005.

[9] Chipchak, J.: A Practical Method of Maintainability Allocation. IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-7, No. 4, pp. 585–589, 1971.

[10] Circle Seal Controls, Inc.: Cartridge Check Valves. C200 Series, 1999.

[11] Civil Aviation Authority: CAP 562. Civil Aircraft Airworthiness Information and Procedures, 2020.

[12] Cooper, T.; Reagan, I.; Porter, C.; Precourt, C.: Global Fleet & MRO Market Forecast Commentary. 2019-2029, 2019.

[13] Denson, W.; Chandler, G.; Crowell, W.; Wanner, R.: Nonelectronical Parts Reliability Data, 1991.

[14] Department of Defense PA: DOD-HDBK-791. Maintainability Design Techniques, 1988.

[15] Department of Defense PA: MIL-HDBK-470A. Designing and developing maintainable products and systems, 1997.

[16] Department of Defense PA: MIL-HDBK-472. Maintainability prediction, 1966.

[17] Department of Defense PA: MIL-STD-721C. Definitions of Terms for Reliability and Maintainability, 1981.

[18] Deutsche Gesetzliche Unfallversicherung: DGUV Information 209-015. Instandhaltung - sicher und praxisgerecht durchführen, 2018.

[19] Eaton Corporation: Aerospace Capabilities. Boeing 777, 2014.

[20] Eaton Corporation: Fluid-Cooled AC Motorpump for Boeing's 747-400, 757, 767 & 777. Model MPEV3-056-6 Series, 2013.

[21] Eaton Corporation: Hydraulic Pressure Switch. 211C223 Series, 2009.

[22] Ebeling, C. E.: An introduction to reliability and maintainability engineering, New York: McGraw Hill, ISBN 0-07-018852-1, 1997.

[23] ExxonMobil: HYJET IV-A PLUS. Safety Data Sheet, 2017.

[24] Francis, G.; Humphreys, I.; Ison, S.; Aicken, M.: Where next for low cost airlines? A spatial and temporal comparative study. Journal of Transport Geography, Vol. 14, No. 2, pp. 83–94, 2006.

[25] GEDORE-Werkzeugfabrik: Gesamtsortiment, 2018.

[26] Gray, D. E.: American Institute of Physics handbook, New York: McGraw-Hill, ISBN 978-0070014855, 1972.

[27] Heisey, R.: 717-200. Aero, No. 19, pp. 18–31, 2002.

[28] Hignett, S.; McAtamney, L.: Rapid Entire Body Assessment (REBA). Applied Ergonomics, Vol. 31, No. 2, pp. 201–205, 2000.

[29] International Air Transport Association: Airline Maintenance Cost Executive Commentary. Edition 2019, 2019.

[30] Korvesis, P.; Besseau, S.; Vazirgiannis, M.: Predictive Maintenance in Aviation: Failure Prediction from Post-Flight Reports. In: pp. 1414–1422.

[31] Lockett, H.; Estefani, J.; Reytérou, É.: An Aircraft Design for Maintainability Methodology Integrated with Computer Aided Design. In: 1st International Through-life Engineering Services Conference. Proceedings, 1st International Through-life Engineering Services Conference, 2012.

[32] Lübben, N.; Rzegotta, I.: Jahresbilanz 2020. Zur Lage der deutschen Luftverkehrswirtschaft, 2021.

[33] Luo, X.; Yang, Y.-m.; Ge, Z.-x.; Wen, X.-s.; Guan, F.-j.: Layout problem of multi-component systems arising for improving maintainability. Journal of Central South University, Vol. 21, No. 5, pp. 1833–1841, 2014.

[34] Mathworks: Surrogate Optimization Algorithm, https://de.mathworks.com/help/gads/surrogate-optimization-algorithm.html (accessed May 5, 2021), 2021.

[35] McAtamney, L.; Hignett, S.: REBA: A Rapied Entire Body Assessment Method for Investigating Work Related Musculoskeletal Disorders. In: Proceedings of Ergonomics Society of Australia Conference, 1995.

[36] McAtamney, L.; Nigel Corlett, E.: RULA: a survey method for the investigation of work-related upper limb disorders. Applied Ergonomics, Vol. 24, No. 2, pp. 91–99, 1993.

[37] Parker Aerospace: Bootstrap Hydraulic Reservoirs, 2009.

[38] Parker Aerospace: Engine-Driven Pumps. Product Catalogue, 2009.

[39] Parker Balston: Sample Filters. Filter Cartridge and Housing Selection.

[40] Pohya, A. A.; Wicke, K.; Hartmann, J.: Comparison of Direct Operating Cost and Life Cycle Cost-Benefit Methods in Aircraft Technology Assessment. In: 2018 AIAA Aerospace Sciences Meeting, 2018 AIAA Aerospace Sciences Meeting, 2018.

[41] Rigby, L. V.; Cooper, J. I.; Spickard, W. A.: Guide to Integrated System Design for Maintainability, 61-424, 1961.

[42] Saltoğlu, R.; Humaira, N.; İnalhan, G.: Aircraft Scheduled Airframe Maintenance and Downtime Integrated Cost Model. Advances in Operations Research, Vol. 2016, pp. 1–12, 2016.

[43] Schröder, V.: Prüfungstrainer Strömungsmechanik. Klausur- und Übungsaufgaben mit vollständigen Musterlösungen. Studium, Wiesbaden: Vieweg+Teubner Verlag / Springer Fachmedien Wiesbaden GmbH Wiesbaden, ISBN 978-3-8348-0988-9, 2010.

[44] Schuivens, M. J. G.: Die historische Entwicklung der Cockpit-Instrumentierungen von Verkehrsflugzeugen. Technische Universität München, PhD thesis, 2015.

[45] Sterkenburg, R.: AIRCRAFT MAINTENANCE & REPAIR. Eigth Edition, MCGRAW-HILL EDUCATION, ISBN 9781260441055, 2019.

[46] Swanson, L.: Linking maintenance strategies to performance. International Journal of Production Economics, Vol. 70, No. 3, pp. 237–244, 2001.

[47] The World Bank Group: GNI per Capita. Atlas Method, https://data.worldbank.org/indicator/NY.GNP.PCAP.CD?year_high_desc=true (accessed December 17, 2020), 2019.

[48] Tinga, T.: Principles of Loads and Failure Mechanisms. Applications in Maintenance, Reliability and Design. Springer Series in Reliability Engineering, London: Springer, ISBN 978-1-4471-4917-0, 2013.

[49] Tinga, T.: Application of physical failure models to enable usage and load based maintenance. Reliability Engineering & System Safety, Vol. 95, No. 10, pp. 1061–1075, 2010.

[50] Tjiparuro, Z.; Thompson, G.: Review of maintainability design principles and their application to conceptual design. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, Vol. 218, No. 2, pp. 103–113, 2004.

[51] Valcor Engineering Corporation: Relief Valves. Product Catalogue, 2020.

[52] Wang, Y.; Shoemaker, C. A.: A General Stochastic Algorithmic Framework for Minimizing Expensive Black Box Objective Functions Based on Surrogate Models and Sensitivity Analysis, 2014.

A Appendix State of the Art

MIL-HDBK-472 Procedure III

Question	Scored Design Factor	Consideration	Score
1	Access (External)	Access adequate both for visual and manipulative tasks	4
		Access adequate for visual, but no manipulative tasks	2
		Access adequate for manipulative, but no visual tasks	2
		Access not adequate for visual or manipulative tasks	0
2	Latches and Fasteners (External)	External latches and/or fasteners are captive, need no special tools, and require only a fraction of a turn for release	4
		External latches and/or fasteners meet two of the above three criteria	2
		External latches and/or fasteners meet one or non of the above three criteria	0
3	Latches and Fasteners (Internal)	Internal latches and/or fasteners are captive, need no special tools, and require only a fraction of a turn for release	4
		lnternal 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
4	Access (Internal)	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
5	Packaging	Internal access to components or parts can be made with no mechanical disassembly	4
		Little disassembly required (less than 3 min)	2
		Considerable disassembly required (more than 3 min)	0
6	Units - Parts (Failed)	Units or parts of plug-in nature	4
		Units or parts of plug-in nature and mechanically held	2
		Units of solder-in nature	2
		Units of solder-in nature and mechanically held	0
7	Visual Displays	Sufficient visual information on the equipment is given within one display area	4
		Two display areas must be consulted to obtain sufficient visual information	2
		More than two areas must be consulted to obtain sufficient visual information	0
8	Fault and Operation Indicators (Built-In Test Equipment)	Fault or malfunction information is provided clearly and for rapid action	4
		Fault or malfunction information is clearly presented, but requires operator interpretation	2
		Fault or malfunction requires no operator interpretation, but is not clearly presented	2
		Fault or malfunction information not clearly presented and requires operator interpretation	0
9	Test Points (Availability)	Task did not require use of test points	4
		Test points available for all needed tests	3
		Test points available for most needed tests	2
		Test points not available for most needed tests	0
10	Test Points (Identification)	All test points are identified with required readings given	4
		Some are suitably marked	2
		Points are not marked and test data are not given	0
11	Labelling	All parts are labelled with full identifying information and all identifying information clearly visible	4
		All parts labelled with full identifying information, but some information is hidden	2
		All information visible, but some parts not fully identified	2
		Some information hidden and some parts not fully identified	0
12	Adjustments	No adjustments or realignment are necessary to place equipment back in operation	4
		A few adjustments, but no major realignments are required	2
		Many adjustments or major realignments must be made	0
13	Testing (In Circuit)	Defective part or component can be determined without removal from the circuit	4
		Testing requires removal	0
14	Protective Devices	Equipment was automatically kept from operating after malfunction occured to to prevent further damage	4
		Indicators warned that malfunction has occurred	2
		No provisions have been made	0
15	Safety (Personnel)	Task did not require work to be performed in close proximity to hazardous conditions (High voltage, radiation, moving parts and/or high temperature parts)	4
		Some delay encountered because of precautions taken	2
		Considerable time consumed because of hazardous conditions	0

Table A.1: Checklist A (Design) of MIL-HDBK-472 Procedure III [16, p. A3-33 ff.].

Score Time [min]	4 0 - 3	2 4 - 7	0 8 and more
Fastener types	Adjustable pawl	Dzus-screw driver slot; Dzus-wing head; Captive - Knurled and slotted head	-
Latch types	Hook-hool latch; Trigger-action latch; Snapslide latch; Hook latch	-	-
Chassis mounted on horizontal shelf (screw fasteners through flange)	-	Captive screw	Screw tapped note with flat washer and lock washer; screw through clearance holes with flat washer, lock washer and nut; Screw through clearance holes with lock nut
Chassis mounted on horizontal shelf (screw fasteners through chassis)	-	Captive screw	Stud through chassis with flat washer, lock washer and nut; Screw into stand-off with flat washer and lock washer
Chassis mounted on vertical rack (screw fasteners into frame)	-	Captive screw	Thumb screw with lock washer and flat washer; Screw into tapped hole with flat washer and lock
Chassis mounted on horizontal shelf (quick-acting fasteners)	Snap-slide latch; Dzus-type fastener; Spring or drawhook latch	-	-
Chassis mounted on vertical rack (quick-acting fasteners)	Push-button latch; Pawl latch 90° turn; Cam-action $90 - 180°$ turn of handle; Adjustable pawl latch	-	-

Table A.2: Proposed scheme for the scoring of questions 1, 2, 3 and 4 of checklist A [6, p. 76].

Desirability	For Physical Access	For Visual Inspection only	For Test and Service Equipment
Most desirable	Pullout shelves or drawers	Opening with no cover	Opening with no cover
Desirable	Hinged door	Scratch-resistant plastic window	Spring-loaded sliding cap
Less desirable	Removable panel with captive, quick-opening fasteners	Scratch-resistant glass	Removable panel with captive, quick-opening fasteners
Least desirable	Removable panel with smallest number of largest screws that will meet requirements	Cover plate with smallest number of largest screws that will meet requirements	Cover plate with smallest number of largest screws that will meet requirements

Table A.3: Recommended equipment accesses [14, p. 4-4].

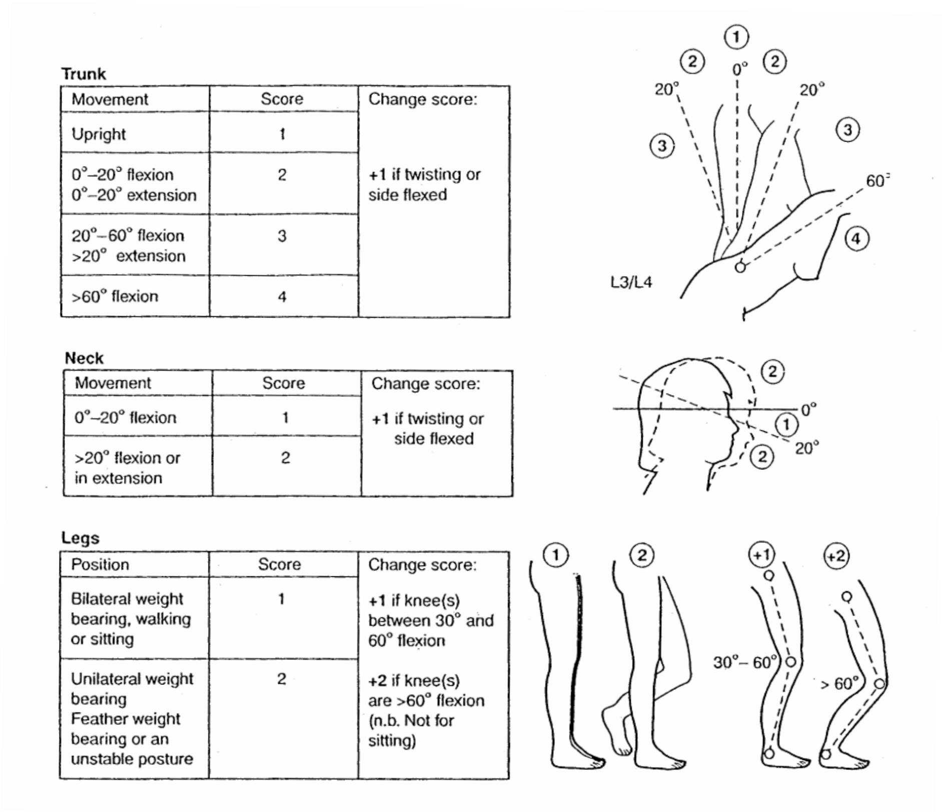
Question	Scored Design Factor	Consideration	Score
1	External Test Equipment	Task accomplishment does not require the use of external test equipment	4
		One piece of test equipment is needed	2
		Several pieces (2 or 3) of test equipment are needed	1
		Four or more items are required	0
2	Connectors	Connectors to test equipment require no special tools, fittings, or adapters	4
		Connectors to test equipment require some special tools, fittings, or adapters (less than two)	2
		Connectors to test equipment require special tools, fittings, and adapters (more than two)	0
3	Jigs or Fixtures	No supplementary materials are needed to perform task	4
		No more than one piece of supplementary material is needed to perform task	2
		Two or more pieces of supplementary material are needed	0
4	Visual Contact	The activities of each member are always visible to the other member	4
		On at least one occasion, one member can see the second, but the reverse is not the case	2
		The activities of one member are hidden from the view of the other on more than one occasion	0
5	Assistance (Operations Personnel)	Task did not require consultation with operations personnel	4
		Some contact was required	2
		Considerable coordination required	0
6	Assistance (Technical Personnel)	Task required only one technician for completion	4
		Two technicians were required	2
		Over two were used	0
7	Assistance (Supervisors or Contractor Personnel)	Task completion did not require consultation with supervisor or contract personnel	4
		Some help needed	2
		Considerable assistance needed	0

Table A.4: Checklist B (Facilities) of MIL-HDBK-472 Procedure III [16, p. A3-47 ff.].

		Question									
		1	2	3	4	5	6	7	8	9	10
Score	**Description**	% of strength	Weight [lbs]	No. of steps	No. of steps	No. of steps	No. of steps	No. of resources	No. of steps	No. of steps	No. of steps
4	Minimum efforts	5	17	3	3	3	3	3	3	3	3
3	Below average efforts	25	35	6	6	6	6	6	6	6	6
2	Average efforts	50	51	9	9	9	9	9	9	9	9
1	Above average efforts	75	86	12	12	12	12	12	12	12	12
0	Maximum efforts	100	150	15	15	15	15	15	15	15	15

Table A.5: Adapted checklist C (Human Factor) of MIL-HDBK-472 Procedure III. Adapted by Bin Wan Husain [6, p. 82].

REBA Body Posture Analysis



Trunk

Movement	Score	Change score:
Upright	1	+1 if twisting or side flexed
0°–20° flexion 0°–20° extension	2	
20°–60° flexion >20° extension	3	
>60° flexion	4	

Neck

Movement	Score	Change score:
0°–20° flexion	1	+1 if twisting or side flexed
>20° flexion or in extension	2	

Legs

Position	Score	Change score:
Bilateral weight bearing, walking or sitting	1	+1 if knee(s) between 30° and 60° flexion
Unilateral weight bearing Feather weight bearing or an unstable posture	2	+2 if knee(s) are >60° flexion (n.b. Not for sitting)

Figure A.1: Scoring of trunk, neck and leg posture for the REBA methodology [28, p. 202].

Table A		Neck											
		1				2				3			
	Legs	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Trunk	1	1	2	3	4	1	2	3	4	1	2	3	4
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table A.6: Table A of the REBA methodology [28, p. 204].

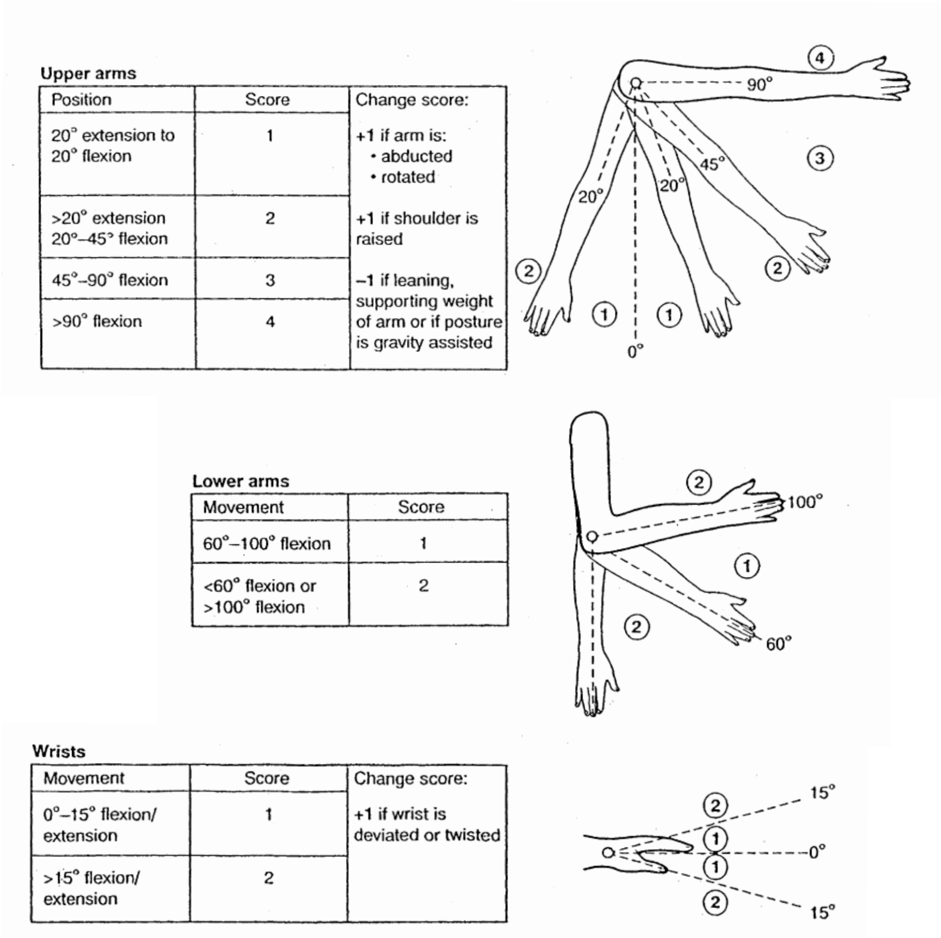


Figure A.2: Scoring of wrist, upper and lower arm posture for the REBA methodology [28, p. 202].

Lifting Mass	$m < 5\,kg$	$5\,kg \leq m \geq 10\,kg$	$10\,kg > m$
Load Factor	0	1	2

Table A.7: Load Factor of the REBA methodology [28, p. 204].

Table B		**Lower Arm**					
		1			**2**		
	Wrist	**1**	**2**	**3**	**1**	**2**	**3**
Upper Arm	**1**	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table A.8: Table B of the REBA methodology [28, p. 204].

0 Good	1 Fair	2 Poor	3 Unacceptable
Well-fitting handle and a mid-range, power grip	Hand hold acceptable but not ideal or coupling is acceptable via another part of the body	Hand hold not acceptable, although possible	Awkward, unsafe grip, no handles Coupling is unacceptable using other parts of the body

Table A.9: Coupling factor of the REBA methodology [28, p. 204].

Table C		**Score B**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Score A	**1**	1	1	1	2	3	3	4	5	6	7	7	7
	2	1	2	2	3	4	4	5	6	6	7	7	8
	3	2	3	3	3	4	5	6	7	7	8	8	8
	4	3	4	4	4	5	6	7	8	8	9	9	9
	5	4	4	4	5	6	7	8	8	9	9	9	9
	6	6	6	6	7	8	8	9	9	10	10	10	10
	7	7	7	7	8	9	9	9	10	10	11	11	11
	8	8	8	8	9	10	10	10	10	10	11	11	11
	9	9	9	9	10	10	10	11	11	11	12	12	12
	10	10	10	10	11	11	11	11	12	12	12	12	12
	11	11	11	11	11	12	12	12	12	12	12	12	12
	12	12	12	12	12	12	12	12	12	12	12	12	12

Table A.10: Table C of the REBA methodology [28, p. 205].

B Appendix Methodology

Input System

system

1x5 struct with 4 fields

Fields	Nr	Name	Type	Component
1	1	'Hydraulic Filter'	'Filter'	*1x1 filter_comp*
2	2	'Relief Valve'	'Valve'	*1x1 valve*
3	3	'Reservoir'	'Reservoir'	*1x1 reservoir*
4	4	'AC Motor Pump'	'Pump'	*1x1 pump*
5	5	'Sample Valve'	'Valve'	*1x1 valve*

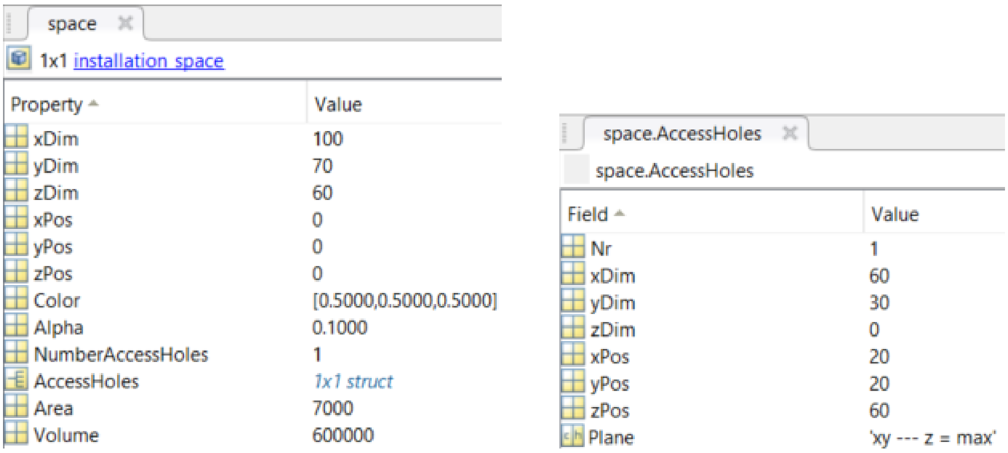
(a) Variable *system*

system(5).Component

Property	Value
Color	[0.1608,0.6902,1]
Kj1	3
Name	'Sample Valve'
Failure_rate	4.5000e-07
xDim	4
yDim	6
zDim	8
Weight	0.2000
xPos	10
yPos	42
zPos	51
xPosChangeable	0
yPosChangeable	30
zPosChangeable	30
connected	*[ ]*
NrConnections	1
SystemType	'hydraulic'

(b) Field ‘Component’

Figure B.1: Structure of the variable *system* and the field ‘Component’ for the example of component 5.



(a) Variable *space* **(b)** Field 'AccesHoles'

Figure B.2: Structure of the variable *space* and the field 'AccessHoles'.

Nr.	Name	Component Type	System	Module	Dimension		Mass		Failure Rate per 10^6 flight hour	
1	Reservoir Shut-Off Valve	Valve	P	-	$4\,x\,6\,x\,8\,cm$		$0.15\,kg$		31.6611	[13, p. 2-159]
2	Filter 1 Press. Mod.	Filter	P	Pressurization Module	$3\,x\,3\,x\,9\,cm$	[39, p. 4]	$0.15\,kg$		0.0499	[13, p. 2-89]
3	Filter 2 Press. Mod.	Filter	P	Pressurization Module	$3\,x\,3\,x\,9\,cm$	[39, p. 4]	$0.15\,kg$		0.0499	[13, p. 2-89]
4	Check Valve 1 Press. Mod.	Valve	P	Pressurization Module	$5\,x\,5\,x\,6\,cm$	[10, p. 2]	$0.48\,kg$	[10, p. 2]	0.4447	[13, p. 2-158]
5	Check Valve 2 Press. Mod.	Valve	P	Pressurization Module	$5\,x\,5\,x\,6\,cm$	[10, p. 2]	$0.48\,kg$	[10, p. 2]	0.4447	[13, p. 2-158]
6	Manual Bleed Valve	Valve	P	Pressurization Module	$4\,x\,6\,x\,8\,cm$		$0.4\,kg$		1.2063	[13, p. 2-158]
7	Reservoir Press. Switch	Pressure Switch	P	-	$3\,x\,3\,x\,9\,cm$	[21, p. 2]	$0.113\,kg$	[21, p. 2]	31.6646	[13, p. 2-132]
8	Reservoir Press. Relief Valve	Valve	P	-	$4\,x\,4\,x\,8\,cm$		$0.0998\,kg$	[51, p.1]	7.7949	[13, p. 2-158]
9	Hydraulic Reservoir	Reservoir	H	-	$37\,x\,37\,x\,37\,cm$	[37, p. 2]	$28.57\,kg$	[37, p. 2]	62.2653	[13, p. 2-142]
10	Sample Valve	Valve	H	-	$4\,x\,6\,x\,8\,cm$		$0.15\,kg$		29.2432	[13, p. 2-154]
11	Drain Valve	Valve	H	-	$4\,x\,6\,x\,8\,cm$		$0.15\,kg$		29.2432	[13, p. 2-154]
12	AC Motor Pump	Pump	H	-	$23\,x\,23\,x\,49\,cm$	[20, p. 3]	$10\,kg$		121.4419	[13, p. 2-105]
13	Relief Valve	Valve	H	Return Filter Module	$4\,x\,4\,x\,8\,cm$		$0.104\,kg$	[51, p.1]	0.7292	[13, p. 2-154]
14	Valve 1 Return Module	Valve	H	Return Filter Module	$4\,x\,4\,x\,8\,cm$		$0.1\,kg$		2.2437	[13, p. 2-151]
15	Valve 2 Return Module	Valve	H	Return Filter Module	$4\,x\,4\,x\,8\,cm$		$0.1\,kg$		2.2437	[13, p. 2-151]
16	Filter Return Module	Filter	H	Return Filter Module	$10\,x\,10\,x\,20\,cm$		$2\,kg$		31.5593	[13, p. 2-89]
17	Filter 1 ACMP Module	Filter	H	ACMP Filter Module	$10\,x\,10\,x\,20\,cm$		$2\,kg$		31.5593	[13, p. 2-89]
18	Filter 2 ACMP Module	Filter	H	ACMP Filter Module	$10\,x\,10\,x\,20\,cm$		$2\,kg$		31.5593	[13, p. 2-89]
19	Valve 1 ACMP Module	Valve	H	ACMP Filter Module	$4\,x\,4\,x\,8\,cm$		$0.1\,kg$		2.2437	[13, p. 2-151]
20	Valve 2 ACMP Module	Valve	H	ACMP Filter Module	$4\,x\,4\,x\,8\,cm$		$0.1\,kg$		2.2437	[13, p. 2-151]

Table B.1: Component list of the reference system containing the sources of the component dimensions and masses. Values marked with (*) are assumptions.

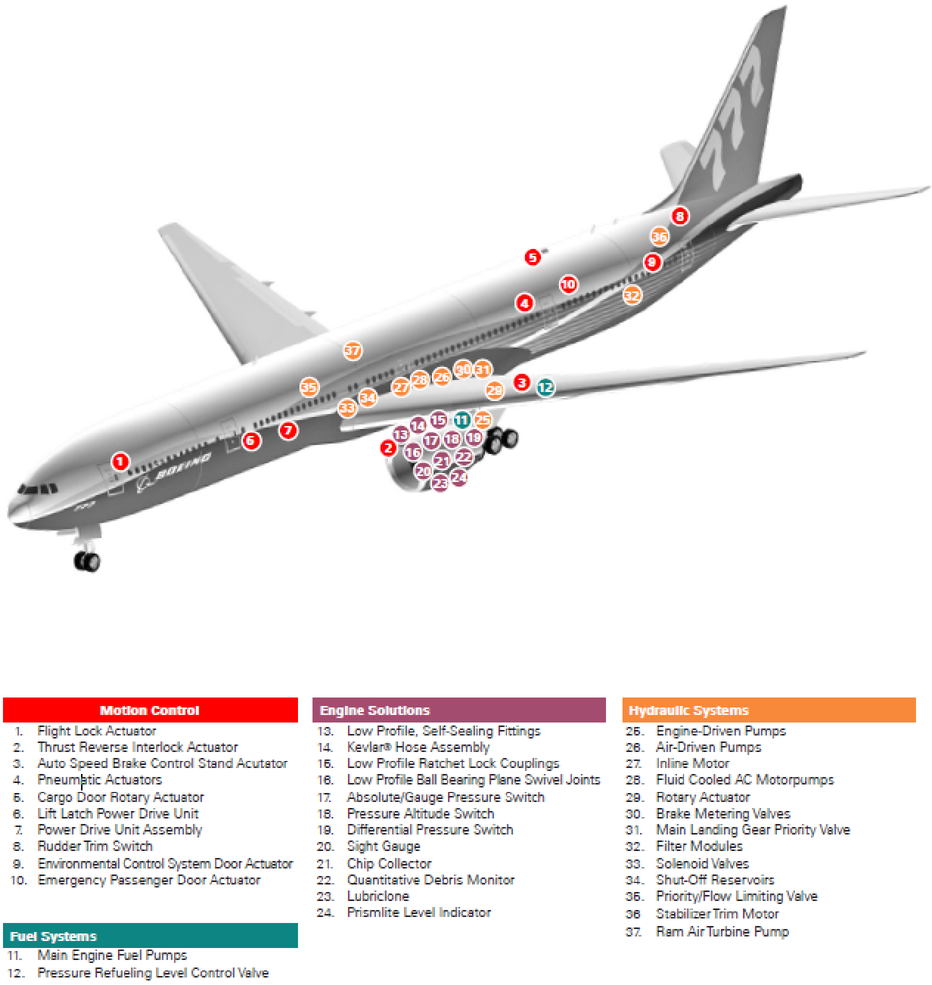


Figure B.3: Rough illustration of the positioning of several hydraulic system components in a Boeing 777 [19, p. 3].

Calculations Connection Length

- **Specifications engine-driven pump** [38, p. 2]
  AP 9VM; $5000\,psi \mathrel{\widehat{=}} 344.74\,bar$; $\dot{m} = 25.1\,g/min$

- **Specifications hydraulic fluid** [23, p. 6]
  HYJET IV-A Plus; $\nu = 10.1\,mm^2/s$; $\rho = 996\,kg/m^3$

- **Specifications air** [43, p. 3]
  $\nu = 15\,mm^2/s \,@\, 40°C$; $\rho = 996\,kg/m^3$

- **Specifications air** [45, chap. 13.18.2.]
  $\dot{V} = 5.66\,m^3/min$; $p = 227.53\,bar$

- **Specifications copper** [26, p. 2-20]
  $\rho = 8950 kg/m^3$

- **Assumptions for the line diameters**
  $d_{elctr} = 10\,mm$; $d_{hydr} = 30\,mm$; $d_{pneum} = 15\,mm$

- **Calculations hydraulic system**

  – Pressure loss per meter hydraulic line:

$$\begin{aligned} w &= \frac{\dot{V}}{A} = \frac{\dot{m}}{\frac{\pi}{4} \cdot d_{hydr}^2 \cdot \rho_{hydr}} \\ &= \frac{25.1\,g/min}{\frac{\pi}{4} \cdot (30\,mm)^2 \cdot 996\,kg/m^3} \\ &= 5.94 \cdot 10^{-4} m/s \end{aligned} \tag{B.1a}$$

$$\begin{aligned} Re &= \frac{w \cdot d_{hydr}}{\nu} \\ &= \frac{5.94 \cdot 10^{-4}\,m/s \cdot 30\,mm}{10.1\,mm^2/s} \\ &= 1.76 \leq 2320 \end{aligned} \tag{B.1b}$$

$$\begin{aligned} \lambda &= \frac{64}{Re} \\ &= \frac{64}{1.76} \\ &= 36.26 \end{aligned} \tag{B.1c}$$

$$\begin{aligned} \Delta p &= \lambda \cdot \frac{l}{d} \cdot \frac{\rho_{hydr}}{2} \cdot w^2 \\ &= 36.26 \cdot \frac{1\,m}{30\,mm} \cdot \frac{996\,kg/m^3}{2} \cdot (5.94 \cdot 10^{-4}\,m/s)^2 \\ &= 2.12 \cdot 10^{-6}\,bar \end{aligned} \tag{B.1d}$$

- Mass hydraulic fluid per meter hydraulic line:

$$\begin{aligned} V_{hydr} &= \frac{\pi}{4} \cdot d_{hydr}^2 \cdot l \\ &= \frac{\pi}{4} \cdot (30\,mm)^2 \cdot 1\,m \\ &= 7.069 \cdot 10^{-4}\,m^3 \end{aligned} \tag{B.2a}$$

$$\begin{aligned} m_{hydr} &= V_{hydr} \cdot \rho_{hydr} \\ &= 7.069 \cdot 10^{-4}\,m^3 \cdot 996\,kg/m^3 \\ &= 0.704\,kg \end{aligned} \tag{B.2b}$$

- **Calculations pneumatic system**
  - Pressure loss per meter pneumatic line:

$$\begin{aligned} w &= \frac{\dot{V}}{A} = \frac{\dot{V}}{\frac{\pi}{4} \cdot d_{pneum}^2} \\ &= \frac{5.66\,m^3/min}{\frac{\pi}{4} \cdot (15\,mm)^2} \\ &= 533.82\,m/s \end{aligned} \tag{B.3a}$$

$$\begin{aligned} Re &= \frac{w \cdot d_{pneum}}{\nu} \\ &= \frac{533.82\,m/s \cdot 15\,mm}{15\,mm^2/s} \\ &= 1067640 \geq 10^5 \end{aligned} \tag{B.3b}$$

$$\begin{aligned} \lambda &= 0.0032 + 0.221 \cdot Re^{-0.237} \\ &= 0.0032 + 0.221 \cdot 1067640^{-0.237} \\ &= 0.011 \end{aligned} \tag{B.3c}$$

$$\begin{aligned} \Delta p &= \lambda \cdot \frac{l}{d} \cdot \frac{\rho_{air}}{2} \cdot w^2 \\ &= 0.011 \cdot \frac{1\,m}{15\,mm} \cdot \frac{1.2\,kg/m^3}{2} \cdot (533.82\,m/s)^2 \\ &= 1.303\,bar \end{aligned} \tag{B.3d}$$

  - Mass air per meter pneumatic line:

$$\begin{aligned} V_{air} &= \frac{\pi}{4} \cdot d_{pneum}^2 \cdot l \\ &= \frac{\pi}{4} \cdot (15\,mm)^2 \cdot 1\,m \\ &= 1.77 \cdot 10^{-4}\,m^3 \end{aligned} \tag{B.4a}$$

$$\begin{aligned} m_{air} &= V_{air} \cdot \rho_{air} \\ &= 1.77 \cdot 10^{-4}\,m^3 \cdot 1.2\,kg/m^3 \\ &= 2.12 \cdot 10^{-4} kg \end{aligned} \tag{B.4b}$$

- **Calculations electronic system**
  - Mass copper per meter electronic line:

$$\begin{aligned} V_{Cu} &= \frac{\pi}{4} \cdot d_{electr}^2 \cdot l \\ &= \frac{\pi}{4} \cdot (10\,mm)^2 \cdot 1\,m \\ &= 7.85 \cdot 10^{-5}\,m^3 \end{aligned} \tag{B.5a}$$

$$\begin{aligned} m_{Cu} &= V_{Cu} \cdot \rho_{Cu} \\ &= 7.85 \cdot 10^{-5}\,m^3 \cdot 8950\,kg/m^3 \\ &= 0.703 \cdot 10^{-4} kg \end{aligned} \tag{B.5b}$$

	Hydraulic	Pneumatic	Electronic
Δp per meter	$2.12 \cdot 10^{-6}\,bar$ +	$1.303\,bar$ -	None +
m per meter	$0.704\,kg$ -	$2.12 \cdot 10^{-4}\,kg$ +	$0.703\,kg$ -
Summary	-> Negligible pressure loss compared to the system pressure -> Mass comparable to electronic system	-> More significant pressure loss compared to system pressure -> Lower mass than hydraulic and electronic lines	-> No pressure loss but resistance grows with line length -> Mass comparable to hydraulic system

Table B.2: Comparison of the advantages and disadvantages of growing line length in different system types.

Body Posture Analysis of the Self-Developed Procedure

Case		Posture	Working Height	Score A	Score B	Height Penalty
1	1	Working height above eye height	$h_{w,\,real} > 164\,cm$	2	4	1
1	2	Working height between eye and shoulder height	$144\,cm < h_{w,\,real} \leq 164\,cm$	2	5	0
1	3	Working height between shoulder height standing and shoulder height while kneeing	$89\,cm < h_{w,\,real} \leq 144\,cm$	3	4	0
1	4	Working height below shoulder height while kneeing	$h_{w,\,real} \leq 89\,cm$	3	4	0
2	1	Working height above shoulder height	$h_{w,\,real} > 144\,cm$	5	5	1
2	2	Working height between shoulder and hip height	$107\,cm < h_{w,\,real} \leq 144\,cm$	5	5	0
2	3	Working height below hip height	$h_{w,\,real} \leq 107\,cm$	6	5	0
3	1	Working height above maximum reachable height	$h_{w,\,real} > 210\,cm$	4	5	1
3	2	Working height between max. reachable height and body height	$176\,cm < h_{w,\,real} \leq 210\,cm$	4	5	0
3	3	Working height between body height and height of a lying person	$51\,cm < h_{w,\,real} \leq 176\,cm$	4	5	0

Table B.3: Considered body postures and the associated REBA scores A and B as well as the height penalty. Height limits are based on statistical body measures [41, p. 144 ff.].

Case		Neck	Trunk	Legs
1	1	1 slight flexion $< 20°$	2 slight flexion $< 20°$	1 bilateral weight, slight flexion
1	2	1 slight flexion $< 20°$	2 slight flexion $< 20°$	1 bilateral weight, slight flexion
1	3	1 slight flexion $< 20°$	2 slight flexion $< 20°$	2 bilateral weight, knees bent
1	4	1 slight flexion $< 20°$	2 slight flexion $< 20°$	2 bilateral weight, knees bent
2	1	2 flexion $> 20°$	4 flexion $> 60°$	1 bilateral weight, slight flexion
2	2	2 flexion $> 20°$	4 flexion $> 60°$	1 bilateral weight, slight flexion
2	3	2 flexion $> 20°$	4 flexion $> 60°$	2 bilateral weight, knees bent
3	1	2 in extension	3 $< 20°$ extension	1 bilateral weight, slight flexion
3	2	2 in extension	3 $< 20°$ extension	1 bilateral weight, slight flexion
3	3	2 in extension	3 0°-20° extension	2 bilateral weight, knees bent

Table B.4: REBA neck, trunk and leg scores for the postures considered in table B.3.

Case		Upper Arm	Lower Arm	Wrist
1	1	3 45° - 90° flexion	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
1	2	4 flexion $> 90°$	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
1	3	3 45° - 90° flexion	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
1	4	3 45° - 90° flexion	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
2	1	4 flexion $> 90°$	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
2	2	4 flexion $> 90°$	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
2	3	4 flexion $> 90°$	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
3	1	4 flexion $> 90°$	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
3	2	4 flexion $> 90°$	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$
3	3	4 flexion $> 90°$	2 flexion $< 60°$ or $> 100°$	1 flexion $\pm 15°$

Table B.5: REBA upper arm, lower arm and wrist scores for the postures considered in table B.3.

C Appendix Results

Reference System

Nr.	Name	x-Position $[cm]$	y-Position $[cm]$	z-Position $[cm]$
10001	Reservoir Pressurization Module	30	54	50
10002	Return Filter Module	50	0	20
10003	ACMP Filter Module	130	15	15
1	Reservoir Shut-Off Valve	10	50	50
7	Reservoir Pressure Switch	72	54	50
8	Reservoir Pressure Relief Valve	78	54	50
9	Reservoir	83	20	25
10	Sample Valve	121	35	30
11	Drain Valve	100	38	15
12	AC Motor Pump	127	5	45

Table C.1: Component positions for the reference system

MIL-HDBK-472 Procedure III

Maintainability Prediction

Nr.	C_{A4}	C_{A5}	C_{B3}	C_{B6}	C_{C1}	C_{C2}	C_{steps}	Accessibility Percentage	MCT $[min]$	R_{pj} $[min]$
10001	2	4	4	4	3	4	3	80.77	23.69	11.14
10002	2	4	4	4	3	4	3	80.77	23.69	22.29
10003	4	0	4	4	3	3	1	48.08	38.80	37.14
1	2	4	4	4	3	4	3	80.77	23.69	18.57
7	2	4	4	4	3	4	3	80.77	23.69	18.57
8	2	4	4	4	3	4	3	80.77	23.69	18.57
9	4	2	4	4	3	1	2	61.54	30.47	29.72
10	4	4	4	4	3	4	3	84.62	21.11	18.57
11	4	4	4	4	3	4	3	84.62	21.11	18.57
12	4	0	4	4	3	3	0	34.62	46.27	35.29
Total System	3	3	4	4	3	3.5	2.4	71.73	276.22	228.43

Table C.2: Automatically evaluated scores, accessibility percentage, MCT and R_{pj} for the reference system.

Optimization

Nr.	x-Position $[cm]$	y-Position $[cm]$	z-Position $[cm]$
10001	10	34	30
10002	50	10	20
10003	130	10	0
1	15	42	50
7	52	34	30
8	58	34	30
9	78	14	38
10	121	35	30
11	116	48	1
12	117	6	41

Table C.3: Component positions for the reference system after optimization with regard to Procedure III. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	C_{A4}	C_{A5}	C_{B3}	C_{B6}	C_{C1}	C_{C2}	C_{steps}	Accessibility Percentage	MCT $[min]$	R_{pj} $[min]$
10001	4	4	4	4	3	4	3	84.62	21.11	10.56
10002	4	4	4	4	3	4	3	84.62	21.11	21.12
10003	4	4	4	4	3	3	3	82.69	21.64	21.12
1	4	4	4	4	3	4	3	84.62	21.11	17.60
7	4	4	4	4	3	4	3	84.62	21.11	17.60
8	4	4	4	4	3	4	3	84.62	21.11	17.60
9	4	4	4	4	3	1	3	78.85	22.76	21.12
10	4	4	4	4	3	4	3	84.62	21.11	17.60
11	4	4	4	4	3	4	3	84.62	21.11	17.60
12	4	0	4	4	3	3	0	34.62	46.27	33.44
Total System	4	3.6	4	4	3	3.5	2.7	78.85	238.41	195.37

Table C.4: Automatically evaluated scores, accessibility percentage, MCT and R_{pj} for the reference system after optimization with regard to Procedure III. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Self-Developed Procedure

Maintainability Prediction

Nr.	$C_{geo,\,i}$	$C_{acc,\,i}$	$C_{HF,\,i}$	$C_{total,\,i}$
10001	7.67	6.00	6.17	6.61
10002	7.00	6.00	6.17	6.39
10003	7.67	4.80	6.33	6.27
1	7.67	6.40	6.33	6.80
7	8.00	6.40	6.33	6.91
8	8.00	6.40	6.33	6.91
9	7.67	6.00	5.17	6.28
10	7.67	8.20	6.50	7.46
11	8.00	8.20	6.50	7.57
12	7.00	4.20	5.50	5.57
Total System	7.63	6.26	6.13	6.68

Table C.5: Checklist scores and total scores of the self-developed procedure for the reference system. Performed without weighting.

Nr.	$C_{fit,\,i}$	C_{vol}	$C_{ConLength,\,i}$
10001	10	4	9
10002	10	4	7
10003	10	4	9
1	10	4	9
7	10	4	10
8	10	4	10
9	10	4	9
10	10	4	9
11	10	4	10
12	8	4	9

Geometry checklist

Nr.	$C_{hapt,\,i}$	$C_{vis,\,i}$	$C_{pack,\,i}$	$C_{space,\,i}$	$C_{NrCon,\,i}$
10001	10	1	10	1	8
10002	10	1	10	1	8
10003	10	4	8	1	1
1	10	1	10	1	10
7	10	1	10	1	10
8	10	1	10	1	10
9	10	8	9	1	2
10	10	10	10	1	10
11	10	10	10	1	10
12	9	4	1	1	6

Accessibility checklist

Nr.	$C_{overhead}$	$C_{mass,\,i}$	$C_{size,\,i}$	$C_{AccSize}$	$C_{dist,\,i}$	$C_{post,\,i}$
10001	1	10	10	1	8	7
10002	1	10	10	1	8	7
10003	1	10	10	1	9	7
1	1	10	10	1	8	8
7	1	10	10	1	8	8
8	1	10	10	1	8	8
9	1	6	10	1	8	5
10	1	10	10	1	9	8
11	1	10	10	1	9	8
12	1	10	8	1	8	5

Human factor checklist

Table C.6: Checklists of the self-developed procedure for the reference system. Performed without weighting.

Optimization

Nr.	x-Position [cm]	y-Position [cm]	z-Position [cm]
10001	34	34	45
10002	45	18	10
10003	124	5	19
1	17	32	39
7	80	37	52
8	78	45	50
9	84	10	39
10	101	15	20
11	100	36	18
12	121	2	44

Table C.7: Component positions for the reference system after optimization with regard to the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{geo,\,i}$	$C_{acc,\,i}$	$C_{HF,\,i}$	$C_{total,\,i}$
10001	8.00	8.80	6.17	7.66
10002	7.33	8.80	6.33	7.49
10003	8.00	5.40	6.33	6.58
1	8.00	9.60	6.50	8.03
7	8.33	8.20	6.33	7.62
8	8.33	8.20	6.33	7.62
9	8.00	6.20	5.17	6.46
10	8.00	9.60	6.50	8.03
11	8.00	9.60	6.50	8.03
12	7.33	4.80	5.50	5.88
Total System	7.93	7.92	6.17	7.34

Table C.8: Checklist scores and total scores for the reference system after optimization with regard to the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{fit,\,i}$	C_{vol}	$C_{ConLength,\,i}$
10001	10	5	9
10002	10	5	7
10003	10	5	9
1	10	5	9
7	10	5	10
8	10	5	10
9	10	5	9
10	10	5	9
11	10	5	9
12	8	5	9

Geometry checklist

Nr.	$C_{hapt,\,i}$	$C_{vis,\,i}$	$C_{pack,\,i}$	$C_{space,\,i}$	$C_{NrCon,\,i}$
10001	10	10	10	6	8
10002	10	10	10	6	8
10003	10	6	9	1	1
1	10	10	10	8	10
7	10	10	10	1	10
8	10	10	10	1	10
9	10	10	8	1	2
10	10	10	10	8	10
11	10	10	10	8	10
12	10	6	1	1	6

Accessibility checklist

Nr.	$C_{overhead}$	$C_{mass,\,i}$	$C_{size,\,i}$	$C_{AccSize}$	$C_{dist,\,i}$	$C_{post,\,i}$
10001	1	10	10	1	8	7
10002	1	10	10	1	9	7
10003	1	10	10	1	9	7
1	1	10	10	1	9	8
7	1	10	10	1	8	8
8	1	10	10	1	8	8
9	1	6	10	1	8	5
10	1	10	10	1	9	8
11	1	10	10	1	9	8
12	1	10	8	1	8	5

Human factor checklist

Table C.9: Checklists for the reference system after optimization with regard to the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Checklist Weighting

Nr.	x-Position [cm]	y-Position [cm]	z-Position [cm]
10001	34	34	44
10002	46	15	11
10003	122	8	1
1	15	38	38
7	89	39	62
8	96	43	63
9	83	1	34
10	101	18	15
11	104	39	13
12	120	0	50

Table C.10: Component positions for the reference system after optimization with regard to the self-developed procedure. $W_{geo} = 1$, $W_{acc} = 10$ and $W_{HF} = 10$, no component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{geo,\,i}$	$C_{acc,\,i}$	$C_{HF,\,i}$	$C_{total,\,i}$
10001	7.67	9.20	6.17	53.78
10002	7.33	8.80	6.33	52.89
10003	7.67	5.80	6.50	43.56
1	7.67	9.60	6.50	56.22
7	7.67	8.20	6.33	51.00
8	8.00	8.20	6.33	51.11
9	7.67	5.40	5.17	37.78
10	7.67	9.60	6.50	56.22
11	7.33	9.60	6.50	56.11
12	7.00	4.80	5.50	36.67
Total System	7.57	7.92	6.18	7.08

Table C.11: Checklist scores and total scores for the reference system after optimization with regard to the self-developed procedure. $W_{geo} = 1$, $W_{acc} = 10$ and $W_{HF} = 10$, no component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{fit,i}$	C_{vol}	$C_{ConLength,i}$
10001	10	4	9
10002	10	4	8
10003	10	4	9
1	10	4	9
7	10	4	9
8	10	4	10
9	10	4	9
10	10	4	9
11	10	4	8
12	8	4	9

Geometry checklist

Nr.	$C_{hapt,i}$	$C_{vis,i}$	$C_{pack,i}$	$C_{space,i}$	$C_{NrCon,i}$
10001	10	10	10	8	8
10002	10	10	10	6	8
10003	10	7	10	1	1
1	10	10	10	8	10
7	10	10	10	1	10
8	10	10	10	1	10
9	10	8	6	1	2
10	10	10	10	8	10
11	10	10	10	8	10
12	10	6	1	1	6

Accessibility checklist

Nr.	$C_{overhead}$	$C_{mass,i}$	$C_{size,i}$	$C_{AccSize}$	$C_{dist,i}$	$C_{post,i}$
10001	1	10	10	1	8	7
10002	1	10	10	1	9	7
10003	1	10	10	1	10	7
1	1	10	10	1	9	8
7	1	10	10	1	8	8
8	1	10	10	1	8	8
9	1	6	10	1	8	5
10	1	10	10	1	9	8
11	1	10	10	1	9	8
12	1	10	8	1	8	5

Human factor checklist

Table C.12: Checklists for the reference system after optimization with regard to the self-developed procedure. $W_{geo} = 1$, $W_{acc} = 10$ and $W_{HF} = 10$, no component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	x-Position $[cm]$	y-Position $[cm]$	z-Position $[cm]$
10001	19	46	46
10002	49	20	34
10003	124	4	20
1	26	33	45
7	62	46	50
8	78	45	50
9	83	13	32
10	101	22	18
11	96	39	15
12	121	0	45

Table C.13: Component positions for the reference system after optimization with regard to the self-developed procedure. $W_{geo} = 10$, $W_{acc} = 1$ and $W_{HF} = 1$, no component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{geo,\,i}$	$C_{acc,\,i}$	$C_{HF,\,i}$	$C_{total,\,i}$
10001	8.67	7.60	6.17	33.48
10002	8.33	9.20	6.17	32.90
10003	8.33	5.40	6.33	31.69
1	8.67	8.60	6.33	33.87
7	8.67	9.00	6.33	34.00
8	8.67	8.20	6.33	33.73
9	8.33	6.20	5.17	31.57
10	8.33	9.20	6.50	33.01
11	8.33	9.00	6.50	32.94
12	7.67	4.80	5.50	28.99
Total System	8.40	7.72	6.13	8.15

Table C.14: Checklist scores and total scores for the reference system after optimization with regard to the self-developed procedure. $W_{geo} = 10$, $W_{acc} = 1$ and $W_{HF} = 1$, no component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{fit,\,i}$	C_{vol}	$C_{ConLength,\,i}$
10001	10	6	10
10002	10	6	9
10003	10	6	9
1	10	6	10
7	10	6	10
8	10	6	10
9	10	6	9
10	10	6	9
11	10	6	9
12	8	6	9

Geometry checklist

Nr.	$C_{hapt,\,i}$	$C_{vis,\,i}$	$C_{pack,\,i}$	$C_{space,\,i}$	$C_{NrCon,\,i}$
10001	10	7	10	3	8
10002	10	10	10	8	8
10003	10	6	9	1	1
1	10	10	10	3	10
7	10	10	10	5	10
8	10	10	10	1	10
9	10	10	8	1	2
10	10	10	10	6	10
11	10	10	10	5	10
12	10	6	1	1	6

Accessibility checklist

Nr.	$C_{overhead}$	$C_{mass,\,i}$	$C_{size,\,i}$	$C_{AccSize}$	$C_{dist,\,i}$	$C_{post,\,i}$
10001	1	10	10	1	8	7
10002	1	10	10	1	8	7
10003	1	10	10	1	9	7
1	1	10	10	1	8	8
7	1	10	10	1	8	8
8	1	10	10	1	8	8
9	1	6	10	1	8	5
10	1	10	10	1	9	8
11	1	10	10	1	9	8
12	1	10	8	1	8	5

Human factor checklist

Table C.15: Checklists for the reference system after optimization with regard to the self-developed procedure. $W_{geo} = 10$, $W_{acc} = 1$ and $W_{HF} = 1$, no component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Component Weighting

Nr.	$C_{geo,\,i}$	$C_{acc,\,i}$	$C_{HF,\,i}$	$C_{total,\,i}$
10001	7.67	6.00	6.17	6.61
10002	7.00	6.00	6.17	6.39
10003	7.67	4.80	6.33	6.27
1	7.67	6.40	6.33	6.80
7	8.00	6.40	6.33	6.91
8	8.00	6.40	6.33	6.91
9	7.67	6.00	5.17	6.28
10	7.67	8.20	6.50	7.46
11	8.00	8.20	6.50	7.57
12	7.00	4.20	5.50	5.57
Total System	7.46	5.76	5.89	6.37

Table C.16: Checklist scores and total scores of the self-developed procedure for the reference system. Performed with component weighting.

Nr.	x-Position $[cm]$	y-Position $[cm]$	z-Position $[cm]$
10001	29	34	50
10002	44	16	15
10003	124	4	20
1	25	42	30
7	62	41	31
8	73	46	51
9	78	11	34
10	103	16	17
11	94	39	16
12	117	5	51

Table C.17: Component positions for the reference system after optimization with regard to the self-developed procedure with component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{geo,\,i}$	$C_{acc,\,i}$	$C_{HF,\,i}$	$C_{total,\,i}$
10001	8.33	8.80	6.17	7.77
10002	8.00	9.20	6.33	7.84
10003	8.33	5.60	6.33	6.76
1	8.33	9.20	6.50	8.01
7	8.33	9.20	6.33	7.96
8	8.33	8.20	6.33	7.62
9	8.33	6.20	5.17	6.57
10	8.33	9.60	6.50	8.14
11	8.33	9.20	6.50	8.01
12	7.67	5.00	5.50	6.06
Total System	8.10	7.11	5.92	7.04

Table C.18: Checklist scores and total scores for the reference system after optimization with regard to the self-developed procedure with component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{fit,\,i}$	C_{vol}	$C_{ConLength,\,i}$
10001	10	6	9
10002	10	6	8
10003	10	6	9
1	10	6	9
7	10	6	9
8	10	6	9
9	10	6	9
10	10	6	9
11	10	6	9
12	8	6	9

Geometry checklist

Nr.	$C_{hapt,\,i}$	$C_{vis,\,i}$	$C_{pack,\,i}$	$C_{space,\,i}$	$C_{NrCon,\,i}$
10001	10	10	10	6	8
10002	10	10	10	8	8
10003	10	6	10	1	1
1	10	10	10	6	10
7	10	10	10	6	10
8	10	10	10	1	10
9	10	10	8	1	2
10	10	10	10	8	10
11	10	10	10	6	10
12	10	7	1	1	6

Accessibility checklist

Nr.	$C_{overhead}$	$C_{mass,\,i}$	$C_{size,\,i}$	$C_{AccSize}$	$C_{dist,\,i}$	$C_{post,\,i}$
10001	1	10	10	1	8	7
10002	1	10	10	1	9	7
10003	1	10	10	1	9	7
1	1	10	10	1	9	8
7	1	10	10	1	8	8
8	1	10	10	1	8	8
9	1	6	10	1	8	5
10	1	10	10	1	9	8
11	1	10	10	1	9	8
12	1	10	8	1	8	5

Human factor checklist

Table C.19: Checklists for the reference system after optimization with regard to the self-developed procedure with component weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Condensed System

Nr.	Name	x-Position $[cm]$	y-Position $[cm]$	z-Position $[cm]$
10001	Reservoir Pressurization Module	20	54	40
10002	Return Filter Module	50	0	10
10003	ACMP Filter Module	70	15	5
1	Reservoir Shut-Off Valve	10	50	40
7	Reservoir Pressure Switch	40	46	40
8	Reservoir Pressure Relief Valve	25	46	40
9	Reservoir	10	5	15
10	Sample Valve	48	25	20
11	Drain Valve	27	20	5
12	AC Motor Pump	70	11	35

Table C.20: Component positions for the condensed system.

MIL-HDBK-472 Procedure III

Maintainability Prediction

Nr.	C_{A4}	C_{A5}	C_{B3}	C_{B6}	C_{C1}	C_{C2}	C_{steps}	Accessibility Percentage	MCT $[min]$	R_{pj} $[min]$
10001	2	0	4	4	3	4	1	46.15	42.47	27.35
10002	2	4	4	4	3	4	3	80.77	23.69	23.44
10003	4	4	4	4	3	3	3	82.69	21.64	23.44
1	2	4	4	4	3	4	3	80.77	23.69	19.53
7	4	4	4	4	3	4	3	84.62	21.11	19.53
8	4	4	4	4	3	4	3	84.62	21.11	19.53
9	4	0	4	4	3	1	0	30.77	48.66	39.07
10	4	4	4	4	3	4	3	84.62	21.11	19.53
11	4	4	4	4	3	4	3	84.62	21.11	19.53
12	4	0	4	4	3	3	0	34.62	46.27	37.11
Total System	3.4	2.8	4	4	3	3.5	2.2	69.42	290.86	248.08

Table C.21: Automatically evaluated scores, accessibility percentage, MCT and R_{pj} for the condensed system.

Optimization

Nr.	x-Position [cm]	y-Position [cm]	z-Position [cm]
10001	32	49	20
10002	48	1	6
10003	69	11	3
1	15	42	36
7	40	42	36
8	20	45	48
9	7	5	14
10	28	5	0
11	17	10	6
12	70	8	32

Table C.22: Component positions for the condensed system after optimization with regard to Procedure III. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	C_{A4}	C_{A5}	C_{B3}	C_{B6}	C_{C1}	C_{C2}	C_{steps}	Accessibility Percentage	MCT [min]	R_{pj} [min]
10001	4	4	4	4	3	4	3	84.62	21.11	10.67
10002	4	4	4	4	3	4	3	84.62	21.11	21.34
10003	4	4	4	4	3	3	3	82.69	21.64	21.34
1	4	4	4	4	3	4	3	84.62	21.11	17.78
7	4	4	4	4	3	4	3	84.62	21.11	17.78
8	4	4	4	4	3	4	3	84.62	21.11	17.78
9	4	0	4	4	3	1	0	30.77	48.66	35.56
10	4	4	4	4	3	4	3	84.62	21.11	17.78
11	4	4	4	4	3	4	3	84.62	21.11	17.78
12	4	0	4	4	3	3	0	34.62	46.27	33.79
Total System	4	3.2	4	4	3	3.5	2.4	74.04	264.31	211.60

Table C.23: Automatically evaluated scores, accessibility percentage, MCT and R_{pj} for the condensed system after optimization with regard to Procedure III. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Self-Developed Procedure

Maintainability Prediction

Nr.	$C_{geo,i}$	$C_{acc,i}$	$C_{HF,i}$	$C_{total,i}$
10001	7.33	5.40	6.17	6.30
10002	7.00	6.00	6.33	6.44
10003	7.33	6.00	6.33	6.56
1	7.33	6.40	6.50	6.74
7	7.67	8.20	6.33	7.40
8	7.33	8.20	6.50	7.34
9	7.00	5.00	5.33	5.78
10	7.33	8.20	6.50	7.34
11	7.33	8.20	6.50	7.34
12	6.33	4.60	5.50	5.48
Total System	7.20	6.62	6.20	6.67

Table C.24: Checklist scores and total scores of the self-developed procedure for the condensed system. Performed without weighting.

Nr.	$C_{fit,\,i}$	C_{vol}	$C_{ConLength,\,i}$
10001	10	3	9
10002	10	3	8
10003	10	3	9
1	10	3	9
7	10	3	10
8	10	3	9
9	10	3	8
10	10	3	9
11	10	3	9
12	8	3	8

Geometry checklist

Nr.	$C_{hapt,\,i}$	$C_{vis,\,i}$	$C_{pack,\,i}$	$C_{space,\,i}$	$C_{NrCon,\,i}$
10001	9	1	8	1	8
10002	10	1	10	1	8
10003	10	8	10	1	1
1	10	1	10	1	10
7	10	10	10	1	10
8	10	10	10	1	10
9	10	7	5	1	2
10	10	10	10	1	10
11	10	10	10	1	10
12	9	6	1	1	6

Accessibility checklist

Nr.	$C_{overhead}$	$C_{mass,\,i}$	$C_{size,\,i}$	$C_{AccSize}$	$C_{dist,\,i}$	$C_{post,\,i}$
10001	1	10	10	1	8	7
10002	1	10	10	1	9	7
10003	1	10	10	1	9	7
1	1	10	10	1	9	8
7	1	10	10	1	8	8
8	1	10	10	1	9	8
9	1	6	10	1	9	5
10	1	10	10	1	9	8
11	1	10	10	1	9	8
12	1	10	8	1	8	5

Human factor checklist

Table C.25: Checklists of the self-developed procedure for the condensed system. Performed without weighting.

Optimization

Nr.	x-Position [cm]	y-Position [cm]	z-Position [cm]
10001	19	44	24
10002	49	11	22
10003	58	21	4
1	15	42	36
7	54	35	39
8	24	43	42
9	10	5	15
10	48	25	20
11	27	20	5
12	69	7	31

Table C.26: Component positions for the condensed system after optimization with regard to the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{geo,\,i}$	$C_{acc,\,i}$	$C_{HF,\,i}$	$C_{total,\,i}$
10001	8.00	7.80	6.33	7.38
10002	8.00	7.80	6.33	7.38
10003	8.00	6.00	6.33	6.78
1	8.00	8.20	6.50	7.57
7	8.00	8.60	6.33	7.64
8	8.00	8.00	6.50	7.50
9	8.00	4.80	5.33	6.04
10	8.00	8.20	6.50	7.57
11	8.00	8.20	6.50	7.57
12	7.00	4.80	5.67	5.82
Total System	7.90	7.24	6.23	7.12

Table C.27: Checklist scores and total scores for the condensed system after optimization with regard to the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.

Nr.	$C_{fit,\,i}$	C_{vol}	$C_{ConLength,\,i}$
10001	10	5	9
10002	10	5	9
10003	10	5	9
1	10	5	9
7	10	5	9
8	10	5	9
9	10	5	9
10	10	5	9
11	10	5	9
12	8	5	8

Geometry checklist

Nr.	$C_{hapt,\,i}$	$C_{vis,\,i}$	$C_{pack,\,i}$	$C_{space,\,i}$	$C_{NrCon,\,i}$
10001	10	10	10	1	8
10002	10	10	10	1	8
10003	10	9	9	1	1
1	10	10	10	1	10
7	10	10	10	3	10
8	10	10	9	1	10
9	10	7	4	1	2
10	10	10	10	1	10
11	10	10	10	1	10
12	10	6	1	1	6

Accessibility checklist

Nr.	$C_{overhead}$	$C_{mass,\,i}$	$C_{size,\,i}$	$C_{AccSize}$	$C_{dist,\,i}$	$C_{post,\,i}$
10001	1	10	10	1	9	7
10002	1	10	10	1	9	7
10003	1	10	10	1	9	7
1	1	10	10	1	9	8
7	1	10	10	1	8	8
8	1	10	10	1	9	8
9	1	6	10	1	9	5
10	1	10	10	1	9	8
11	1	10	10	1	9	8
12	1	10	8	1	9	5

Human factor checklist

Table C.28: Checklists for the condensed system after optimization with regard to the self-developed procedure without weighting. Optimization parameters: $\Delta_{allowed} = 20\,cm$, $e_{max} = 200$.