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THESIS

ANALYSIS OF MAINTENANCE RECORDS TO SUPPORT PREDICTION OF MAINTENANCE REQUIREMENTS IN THE GERMAN ARMY

by

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Today the German armed forces are faced with a broad, varied and graduated range of tasks including missions outside Germany. A major challenge in planning the force structure for missions like the one in Kosovo is to predict the required maintenance capacities. This thesis conducts an exploratory data analysis of maintenance records of the German Army, using the wheeled reconnaissance tank "Luchs" as an example. The question under investigation is whether or not data from the maintenance records can be used to support a future "maintenance prediction tool." It is shown that repairtime distributions extracted from the data can be used to model the repair process in a simulation. The Weibull distribution family, which is commonly used in reliability applications, proved flexible enough to simulate repairtimes and workorder supply times. Implementing these results in a simulation of the repair process will improve the accuracy and quality of the simulation output. In addition, this thesis discusses data quality issues and makes design suggestions for a new maintenance organization software. Data problems can be minimized if the problems identified in this study are aggressively attacked during the design and implementation phases of the new software.

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ANALYSIS OF MAINTENANCE RECORDS TO SUPPORT PREDICTION OF MAINTENANCE REQUIREMENTS IN THE GERMAN ARMY

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requirements for the degree of

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ABSTRACT

Today the German armed forces are faced with a broad, varied and graduated range of tasks including missions outside Germany. A major challenge in planning the force structure for missions like the one in Kosovo is to predict the required maintenance capacities. This thesis conducts an exploratory data analysis of maintenance records of the German Army, using the wheeled reconnaissance tank “Luchs” as an example. The question under investigation is whether or not data from the maintenance records can be used to support a future “maintenance prediction tool.” It is shown that repairtime distributions extracted from the data can be used to model the repair process in a simulation. The Weibull distribution family, which is commonly used in reliability applications, proved flexible enough to simulate repairtimes and workorder supply times. Implementing these results in a simulation of the repair process will improve the accuracy and quality of the simulation output. In addition, this thesis discusses data quality issues and makes design suggestions for a new maintenance organization software. Data problems can be minimized if the problems identified in this study are aggressively attacked during the design and implementation phases of the new software.

THESIS DISCLAIMER

The reader is cautioned that computer programs and codes developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs and codes are free of computational and logic errors, they cannot be considered validated. Any application of these programs and codes without additional verification is at risk of the user.

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EXECUTIVE SUMMARY

In the era of East-West confrontation, the German Army mission was focused on defending the former eastern border of the Federal Republic of Germany against an immediate military threat from Warsaw Pact forces. Force structures and maintenance capabilities were oriented to a full-scale war scenario, based on experiences from former major conflicts like WW II and the Israel-Arabian wars.

Today the Bundeswehr, as an instrument of German security policy, is faced with a broad, varied and graduated range of tasks across the entire spectrum of humanitarian activities, up to and including military combat operations under the Charter of the United Nations. A major challenge in planning the force structure for missions like the one in Kosovo is to predict the required maintenance capacities. One way to make more accurate predictions is the use of simulation. However, the quality and accuracy of predictions obtained by simulation depends not only on the simulation model itself, but even more on the quality of the underlying database.

This thesis conducts an exploratory data analysis of maintenance records of the German Army. The question under investigation is whether or not data from these records can be used to support a future "maintenance prediction tool." The Dornier company has developed a prototype of such a tool within its study "System for Analysis of Maintenance" (SAM-Div) [Ref. 3]. The tool consists of a simulation and a database module. The database module includes equipment-specific parameters like mean time between failures (MTBF), repairtime parameters, or supply statistics. The major recommendation of the SAM-Div study is to replace

the “educated guesses” currently present in the database by evaluating data obtained from maintenance history records or further studies.

This thesis illustrates with the example of the wheeled reconnaissance tank “Luchs” that extracting repairtime distributions from maintenance history records is possible. The Weibull distribution family, which is commonly used in reliability applications, proved flexible enough to simulate these repairtimes. Statistical tests like the “Kolmogorov-Smirnov goodness-of-fit test” and the “generalized likelihood-ratio test” are applied to defend the use of the Weibull distribution. Similar findings apply to spare part supply times, which can be modeled by workorder supply time distributions extracted from the same database. Again, the Weibull distribution family proved to be a suitable choice to simulate these supply times. Implementing these results in a simulation of the repair process will improve the accuracy and quality of the simulation output.

On the other hand, this thesis revealed serious data quality problems within the maintenance history database. The major problem is an immense data loss between the record-generating maintenance facility and the data-collecting agency. The data collection analyzed in this thesis contained only 47 percent of the records generated between 1997 and 2000. This lead to the conclusion that reliability parameters like the mean time between failures (MTBF) cannot be obtained from the database. Another data problem is the high amount of blank or invalid data entries, which is not solely the responsibility of the user who entered the data, but also due to a “bad” design of the maintenance organization software. The design of a new software to be introduced in the near future should be thoroughly evaluated to avoid similar problems. This thesis discusses these data quality issues and recommends software and database design changes. For instance, the new software should employ error-checking mechanisms and a graphical user interface. Furthermore, not all the data fields of a workorder should be contained in the maintenance history database. A careful design decision regarding what information should be included in the database is necessary. With the potential of a dramatic reduction in workorder record size, it is possible to combine the four records, which are currently generated by each workorder, into only one record. This would improve data-handling procedures and enhance analysis possibilities. Data problems can be minimized if the problems identified in this study are aggressively attacked during the design and implementation phases of the new software.

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I. INTRODUCTION

A. OVERVIEW

In the era of East-West confrontation, the German Army mission was focused on defending the former eastern border of the Federal Republic of Germany against an immediate military threat from Warsaw Pact forces. Force structures and maintenance capabilities were oriented to a full-scale war scenario, based on experiences from former major conflicts like WW II and the Israel-Arabian wars.

Today the Bundeswehr, as an instrument of German security policy, is faced with a broad, varied and graduated range of tasks across the entire spectrum of humanitarian activities, up to and including military combat operations under the Charter of the United Nations. The combat intensities of these missions can range from very low (humanitarian and observer missions) to very high (peace-enforcing missions). In many cases, the intensity is hard to predict when planning the structure of the mission force. Furthermore, the climate (e.g. Somalia 1992) and/or the terrain (e.g. Somalia 1992, Kosovo 1999) may be quite different from the ones in Central Europe, for which the current generation of German Army vehicles were designed. The conditions of usage (e.g. mileage per unit time) in such missions are usually quite different from regular peacetime activities [Ref. 1]. All these circumstances have a critical influence on equipment failure rates and thus on the required maintenance capabilities and capacities of the force.

B. BACKGROUND AND PROBLEM STATEMENT

Since the end of the "Cold War" the German Army's maintenance branch has been faced with enormous budget cuts, continuous restructuring and decreasing of its force strength, while at the same time new kinds of missions like Bosnia or Kosovo have to be supported. One difficulty in supporting these missions is to predict how much maintenance capacity, in which maintenance types, is needed to ensure force readiness.

Making the logistics force too large means higher deployment costs and reduced resources for regular support "at home." On the other hand, an undersized logistics structure endangers force readiness and makes "touch ups," often with even higher costs, necessary. Carefully planning the support structure is crucial for the success of a mission. This seems especially important in times in which the Armed Forces logistics is in competition with the civilian defense industry, who offers to ensure supply and maintenance even for missions outside Germany.

Today, this planning is done on expert-based knowledge and experiences gained in recent missions. However, decisions about the required maintenance capabilities and capacities should involve a more quantitative approach by considering the variability in maintenance requirements (scheduled and corrective) for the chosen systems. Currently, the main data source used to support the planning process mentioned above is a catalog ("Materialerhaltungszeiten-Katalog" or short "MEZ-Katalog") from Heeresamt (Office of the Army), in which the annual capacity for maintenance-man hours for various military equipment is specified [Ref. 15]. However, this catalog is based mainly on estimated means. Therefore, data from this catalog can only serve as a rough guide in the planning process.

Another major difficulty in supporting missions outside one's own country is to determine which spare parts and major assemblies should be supplied and stocked in the area of operations [Ref. 1]. Such decisions are currently made by experts based on their knowledge and experiences and with the usage of historical data.

To better deal with these difficulties, the German Army maintenance branch intends to create a "maintenance prediction tool" that can generate forecasts of maintenance demand and required spare parts more accurately [Ref. 2]. The stochastic nature of the repair process requires a simulation approach, in which the variability in demand is adequately reflected within a specified scenario. The Dornier Company conducted a study for the German Army, in which it developed a simulation of the maintenance process in an Army division [Ref. 3]. The study concludes that its *simulation module* could be a suitable tool for the described tasks only if better data could be obtained. Presently, many parameters like failure rates or repairtimes are estimated with "educated guesses." A thorough analysis of available maintenance data is therefore a main recommendation of the Dornier study. In a first step toward this goal, this thesis conducts an exploratory data analysis of German Army workorder records.

C. OBJECTIVE STATEMENT

The objective of this study is to determine, which data, if any from the German Army maintenance records can be used to support a future "maintenance prediction tool."

Conclusions about the distribution of repairtimes of certain equipment and the spare parts which were needed in those repairs are compared to data from the first half of the year 2000 in order to see how well the data can be used in predicting future demands. Furthermore, the analysis presents statements about data quality and deficiencies. These findings may contribute to the formulation of specifications and requirements for the development of new maintenance organization software [Ref. 2].

D. SCOPE AND LIMITATIONS

This thesis analyzes data from German Army maintenance records from 1997 to 1999 and from the first half of the year 2000. It uses the reconnaissance tank "Luchs" as an example, thereby analyzing records of scheduled and corrective maintenance.

E. THESIS OVERVIEW

Chapter II contains a literature review on efforts to predict maintenance demand. Chapter III describes the raw data and the process of importing these raw data into database management software, using Microsoft® Access. The chapter concludes with an analysis on the degree of completeness of the data. Chapter IV documents a repairtime analysis of the "Luchs" data records. The focus lies on the repairtime distributions for different maintenance types. Chapter V deals with spare parts usage and spare part supply times, whereas Chapter VI discusses possibilities and problems associated with the maintenance history of individual vehicles. Chapter VII lists and discusses data quality issues and gives recommendations for future maintenance organization software. Chapter VIII summarizes the results of this study and gives recommendations for further work.

II. LITERATURE REVIEW

A. OVERVIEW

The literature search and review conducted in preparation for this thesis focused on documented efforts to predict maintenance requirements, including the demand for spare parts. Most of the publications that deal with this topic are military related. This is not surprising since after the end of the Cold War many countries restructured their armed forces due to changes in threats, strategies, budgets, or simply downsizing of forces. This need to change structures became especially prominent for logistics support. Whereas the old support system for the forces of the western world was designed mainly to ensure the ability to fight in Central Europe against a known threat, conditions changed dramatically during the 1990's. Nowadays, logistics support for force projections, even into remote parts of the world, must be provided. Furthermore, more and more high-tech weapon systems have special logistical needs and problems. The RAND corporation provides the U.S. military with analytic research on major policy and organizational concerns [Ref. 4]. RAND has conducted many studies which are related to the topics mentioned above. Some of them are described in Section B.

Interestingly, only a limited number of publications deal with civilian applications of predicting maintenance needs. Publications of interest to this study are described in Section C. These publications focus on the theory of maintenance planning.

B. MILITARY RELATED STUDIES

The Dornier Company conducted a study for the German Army, in which it developed a simulation of the maintenance process in an Army division [Ref. 3]. This study is called "System for Analysis of Maintenance (SAM-Div)." The simulation consists of two modules: a *database module* with all the relevant data, and a *simulation module*, which is able to simulate the maintenance process for a German Army division within a specified scenario. The author of the study, Peter Buechen, concludes that the simulation module is a suitable tool to analyze the maintenance process in general; however, it lacks reliable data in the database. He describes a methodology to gradually improve the quality of these data with the help of the database module. He also underlines the necessity to analyze existing maintenance records and to conduct further studies to gain the data, which are necessary to replace the numerous "educated guesses" now present in the database.

With his 1992 NPS Master's Thesis "Decision Aid for Planning the Maintenance of Electronic Equipment in the German Army," Wolfgang Kofer developed a simulation approach to deal with aspects of maintenance prediction [Ref. 5]. By analyzing different decision tools, Kofer identified missing and bad quality data as a general shortcoming. His conclusion was to emphasize the development and continuing maintenance of the necessary databases. A quite similar conclusion is present in Bernard F. Mimms' 1992 NPS Master's Thesis "An Object-Oriented Approach to Reliability and Quality Control Modeling of the Maintenance Effort for U.S. Marine Corps Ground Combat Equipment" [Ref. 6]. Mimms developed an empirically based maintenance forecasting system, in which the forecasting is done by simulating future repair and failure times from models, which were estimated by using available maintenance history data. He states that erroneous and oftentimes missing data limits the effective use of many indicators used in his models. Mimms used exponential repairtime and uptime distributions for his simulation based on Markov Chains.

The RAND analysts also encountered data problems in the majority of their logistics related studies. In 1996, Lionel A. Galway and Christopher H. Hanks prepared a report ("Data Quality Problems in Army Logistics") for the United States Army about this issue. They analyzed many examples of data problems within supply and maintenance [Ref. 7]. Their findings concluded that many problems arise from the fact that the personnel in logistic processes are often not aware of the importance and usage of certain data. The lack of automatic input checks and supervision can then lead to "bad data." Furthermore, the authors saw that one of the primary reasons why data-quality problems occur was that the data was used for purposes not intended or envisioned when they were designed or collected.

A related report underlining the importance of reliable data is RAND's 1995 "Velocity Management" study [Ref. 1]. Velocity Management is an approach to improve the responsiveness and efficiency of the U.S. Army's logistics system. Its goal is to reengineer and to improve support functions by establishing baselines, identifying inefficiencies, setting goals for corrective actions, and measuring performance. Implicit in this approach is the idea that information and data are assets. Using performance data is of central importance for the reengineering and managing of logistics processes. The authors, John Dumond, Rick Eden, and

John Folkeson, found that many performance measures are only reported as averages. The authors state that this practice provides insufficient and in many cases potentially misleading information, whenever the variability of these measures is not considered. This statement is supported with the example of order-and-ship (OST) times of spare parts used to repair Apache attack helicopters.

In another report, "Weapon System Sustainment Management," RAND developed a concept for improving the sustainability of weapon systems to achieve increased weapon system availability at lower costs [Ref. 8, Ref. 9]. The authors, John Dumond, Rick Eden, and John Folkeson, argue that the complexity of modern weapon systems improves their capabilities but also reduces their availability and increases costs. This report proposes a database integrated across time, echelons, and functions, and sustained through the life of the system. Such a database could help identify design problems and "lemons." These are high-tech components that exhibit chronic performance problems. The authors of this RAND report estimate that such components constitute about nine percent of a total set, yet they account for about half of the workload on subcomponents at their respective depot-level repair shops. Such "lemons" also tend to consume about twenty times as many subcomponents in their lifespan than "non-lemon" components of the same design. It is therefore desirable to remove those "lemons" from the system as soon as possible. According to the authors, this could be done by using a database that tracks serial numbers in operational and maintenance history.

"Weapon System Sustainment Management" is one of several proposals the U.S. Army can adopt to improve its future logistics systems. More proposals can be found in RAND's 1994 study, "Precision-Guided Logistics," in which the authors, Marc L. Robbins and Douglas W. McIver, analyzed the support for high-tech weapons in three scenarios, each with a different intensity and duration (*Operation Just Cause* in Panama, *Operations Desert Shield* and *Desert Storm* in Southwest Asia) [Ref. 4]. They used simulation techniques to assess the effectiveness of the U.S Army's logistics system in supporting a mission-critical major assembly of the Apache attack helicopter. An important finding was that forecasting the amount of spare parts needed is quite difficult because of the extreme variability and uncertainty involved in these operations. They concluded that it was infeasible to deploy massive stockpiles of spare parts; the costs of such an approach using high-tech components would be immense. Furthermore, the fluctuations in demand would still cause shortfalls in critical spare parts. This was consistent with findings and conclusions in earlier RAND studies (e.g., "Evaluating the Combat Payoff of Alternative Logistics Structures for High-Technology Subsystems" [Ref. 10]). Among other suggestions, the authors of "Precision-Guided Logistics" recommended strengthening and consolidating Intermediate Repair in a theater support facility. They believe that the combined benefits of batch processing repairs, and prioritizing and concentrating test equipment would raise productivity and create a more responsive repair system.

In parts of their "Precision-Guided Logistics" study the authors used a simulation tool called "Dyna-METRIC Version 6" [Ref. 11]. This tool uses Monte Carlo simulation and was developed within RAND's "Project Air Force" as an assessment model that relates logistics resources and pipelines to wartime readiness and sustainability by modeling and forecasting the demand for aircraft spare parts. Several other reports describe this larger body of work and are listed here (cited from [Ref. 11]):

1. John B. Abell et al., *Estimating Requirements for Aircraft Recoverable Spares and Depot Repair*, RAND, MR-264-AF, 1993.
2. John L. Adams, John B. Abell, and Karen E. Isaacson, *Modeling and Forecasting the Demand for Aircraft Recoverable Spare Parts*, RAND, R-4211-AF/OSD, 1993.
3. John B. Abell and Frederick W. Finnegan, *Data and Data Processing Issues in the Estimation of Requirements for Aircraft Recoverable Spares and Depot Repair*, RAND, R-4211-AF/OSD, 1993.
4. Donald P. Gaver, Karen E. Isaacson, and John B. Abell, *Estimating Aircraft Recoverable Spares Requirements with Cannibalization of Designated Items*, RAND, R-4213-AF, 1993.
5. Karen E. Isaacson and Patricia M. Boren, *Dyna-METRIC Version 6: An Advanced Capability Assessment Model*, RAND, R-4214-AF, 1993.
6. John B. Abell, *Estimating Requirements for Aircraft Recoverable Spares and Depot Repair: Executive Summary*, RAND, MR-4215-AF, 1993.

The first of these reports describes the entire body of work in substantial detail and includes an elementary exposition of the 1993 system. The second report describes improved methods for forecasting the demand for aircraft recoverable spares and for specifying the variance of the probability distribution describing the number of assets of a given type in resupply. The third report discusses data and data processing issues related to estimating aircraft recoverable spares and repair requirements. The fourth report presents a computational algorithm for estimating requirements for aircraft recoverable spares based on the assumption that items can be designated as cannibalizable or not. The fifth describes Dyna-METRIC version 6, and the sixth summarizes the entire body of work.

C. NON-MILITARY LITERATURE

In his book *Maintainability, Availability, & Operational Readiness Engineering* [Ref. 12], Dimitri Kececioglu postulates that once equipment has been purchased, maintenance and repairs cost anywhere from four to forty times the purchase price. He further states that the ability to monitor, quantify, and predict maintenance needs ensures the highest equipment availability at the lowest cost. The author integrates concepts of operational readiness, mission reliability, and adequate design to make the total system effective. His book provides a wide spectrum of preventive maintenance strategies, along with the analytical tools for choosing the most appropriate ones. The extensive discussion of maintainability and its quantification represents a detailed reference for parametric statistical models often used in simulations (e.g., exponential- or Weibull-repairtime distributions).

The book *An Introduction to Predictive Maintenance* by R. Keith Mobley [Ref. 13] provides an in-depth discussion of the benefits of a successfully implemented predictive maintenance strategy compared to a time-driven preventive maintenance management. Among those benefits are reduced maintenance costs, reduced equipment breakdowns, reduced spare parts inventory, reduced equipment downtimes, and increased equipment life spans. According to Mobley, implementing such a program requires substantial investments in both capital and personnel. The adoption of vital record keeping and information-exchange procedures as well as establishing and maintaining a viable database are critical to a program's success. Mobley states that the initial development of a predictive maintenance database may require many staffmonths of effort.

Methods and mathematics of maintenance planning are discussed in Patrick Lyonnet's book, *Maintenance Planning* [Ref. 14]. He describes different maintenance policies and reliability models. In his discussion about data banks for reliability and maintenance, Lyonnet postulates that electronic components usually have constant failure rates and oftentimes a known "Mean Time between Failures (MTBF)." This might be true for single components, but not for electronic subsystems, as the analyses from RAND show.

D. SUMMARY

The literature sources mentioned in the previous sections clearly indicate the major and critical role of reliable and accurate data in predicting and forecasting problems. Many efforts to make reliable predictions suffered or failed due to poor data quality. Uncertainties in environmental factors and scenarios tend to be extremely high in many military applications, with the result of even higher variances in performance measures. RAND has demonstrated that the recording and analysis of means is in most cases insufficient and not informative, and in many cases can lead to false conclusions and policies. Many measurements, especially in military environments, have standard deviations that substantially exceed the mean [Ref. 1].

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III. THE DATA

A. OVERVIEW

This chapter describes the raw data and the process of importing the raw data into database management software, here Microsoft Access. It concludes by analyzing how complete the data are.

The data for this study were collected and supplied by the Army Maintenance School (Aachen/Germany). They are supposed to contain all datafields of all maintenance records for the specified time period. The data of every single workorder are split and arranged as fixed-width fields in four different kinds of text files, called Hx1, Hx2, Hx3, and Hx4. After completion of a workorder, these files are automatically created by the currently used maintenance organization software and sent as hidden files by floppy-disk exchange to the next supply unit. From there, the files are transmitted to data-processing agencies, where they can be analyzed. Appendix A shows an example of a maintenance workorder.

B. RAW DATA

The raw data were supplied on five CD-ROMs and consisted of 16 text files with the maintenance records of 1,379,791 workorders for the years 1997-2000 (the first six months only for 2000). The four different types of text files are described below.

1. Hx1-Files

Every record in these files represents exactly one workorder. The data fields contain information about the equipment unit, the maintenance unit, the item repaired, dates and times, personnel involved, maintenance type and level, or a short description of the work performed. A record consists of 148 data fields and is uniquely identified by its maintenance-unit number and its workorder number. Information from Hx1-records are often used for analyzing the time it takes to accomplish certain tasks, e.g., the time from initiating the maintenance process by writing a workorder to the completion of the repair, or the time from ordering a spare part to its delivery. Although this kind of performance analysis is not a subject of this thesis, Hx1-records are the basis for many of the analyses in this study. A listing of the fieldnames together with data type and length is provided in Appendix B.

2. Hx2-Files

These files contain more detailed information about the work performed, e.g., a vehicle after an accident might have different kinds of damage and work to be done. Every record represents one work position; therefore several Hx2-records might be related to a single Hx1-record. A record consists of 28 data fields and is uniquely identified by the maintenance-unit number in combination with the workorder and position number. A listing of the fieldnames together with data type and length is provided in Appendix B.

3. Hx3-Files

Hx3-records contain detailed information about the spare parts used during the maintenance process. As with the Hx2-records, several Hx3-records might be related to a single Hx1-record because each type of spare part used in a workorder represents one position and thus one Hx3-record. The maintenance-unit number, in combination with the workorder and position number, uniquely identifies every record consisting of 52 data fields. A listing of the fieldnames together with the data type and length is provided in Appendix B.

4. Hx4-Files

These files contain information about major assemblies that were exchanged during a corrective or scheduled maintenance. These assemblies also occur as spare parts in the related Hx3-record. Serial numbers of both the failed and the "good" assemblies could be tracked to gather data over the lifespan of particular assemblies. As in the previous case, more than one Hx4-record can be related to one Hx1-record. For most Hx1-records, however, no related Hx4-record exists because the exchange of major assemblies, like an engine, is not so common. A record consists of 18 data fields and is uniquely identified by the maintenance-unit number together with the workorder and position number. A listing of the fieldnames together with data type and length is provided in Appendix B. Appendix A contains a sample of an Hx4 text file.

C. DATA IMPORT

The data were imported into tables for further analysis using Microsoft® Access 2000. Access has the option to import fixed-width text files. This is supported by an "Import Text

Wizard"; however, Access does not recognize the correct structure of the data records. The reason for this could be that there are many missing values in most of the records. This means that breaks, data types and field lengths have to be specified manually in the import setup specification. Some experience with the data and the maintenance process is required to avoid errors in these import processes. The field names are also specified during the data import, although later changes are possible. Appendix A shows a sample section of a data table and Table 2.1 gives an overview of the imported tables.

Table Name	#Records	#Maintenance Fac.
Hx1_1997	386,787	565
Hx1_1998	361,780	584
Hx1_1999	375,215	637
Hx1_2000	256,009	589
Hx2_1997	1,490,930	
Hx2_1998	1,312,891	
Hx2_1999	1,251,997	
Hx2_2000	843,134	
Hx3_1997	1,062,544	
Hx3_1998	591,177	
Hx3_1999	828,874	
Hx3_2000	617,372	
Hx4_1998	1,424	

Table 3.1 Database Tables. *Description: Text file Hx1_1997 was imported into Table Hx1_1997. It contains 386,787 records, which were generated by 565 maintenance facilities (maintenance levels 2 and 3). Hx4-files other than from 1998 were not imported because the Hx4-data fields are not used within the scope of this study.*

D. A FIRST ANALYSIS

In every maintenance unit, the maintenance organization software generates the workorder numbers consecutively. Hence, the highest workorder number should be equal to the number of workorders for the unit in that year. Slight differences are expected because some workorders from one year are completed in the next year, e.g., a workorder from 1997 (workorder number beginning with "97") might be finished in 1998 and appear in the file "Hx1_1998." The sum of the highest workorder numbers over all units for a certain year should therefore be approximately equal to the number of workorders existent for that year. Table 2.2 compares the theoretical value (sum of the highest workorder numbers) to the existent data.

Year	Theoretical Value	Existent Workorders	Percent
1997	787,237	382,362	48.6%
1998	849,476	336,694	42.2%
1999	890,559	451,068	50.6%
2000	386,769	179,667	46.5%

Table 3.2 Completeness of Data. *Description: In 1997, the sum of the highest workorder numbers over all units yielded a theoretical value of 787,237. Only 382,362 workorder records from 1997 (which is 48.6%) are contained in all of the imported Hx1-files.*

The numbers shown in Table 3.2 lead to the conclusion that merely 50 percent of the data are available for this study. The percentage values shown in Table 3.2 represent upper bounds on the completeness of the data because unless the workorder with the maximum number is included in the data this estimate is low. This data loss is a known problem, which is primarily caused by the floppy disk exchange. However, further analyses should address this problem in order to avoid systematic data losses, at least in the procedures of the next maintenance organization software. For this study, it is assumed that records are missing "at random," so that the data in this thesis represent a simple random sample from the population of all generated data. This is certainly a strong assumption since the sample of data records could be biased in many ways, for instance, workorders with longer repairtimes could have a higher ratio of missing records than those with shorter repairtimes. However, the data are generated and transmitted automatically without human interaction, and there is no indication that records are systematically missing. Only a thorough analysis of the missing workorders in the local archive files of the maintenance units themselves could reveal such patterns, if there are any. With these points in mind, the assumption made above seems justified. The fact that only a fraction of the data is available in this study will be emphasized whenever necessary in the following chapters.

IV. REPAIRTIMES

A. INTRODUCTION AND OVERVIEW

This chapter documents a repairtime analysis of the wheeled reconnaissance tank "Luchs." Section B illustrates repairtime distributions for different maintenance types and analyzes parametric distribution models. Section C analyzes the times associated with scheduled maintenance.

The German Army has been using the "Luchs" quite heavily in its Balkan missions, which means that a broad range of workorders from both scheduled and corrective maintenance can be expected. Thus, the "Luchs" seems to be a well suited and needed example for a thorough data analysis. Furthermore, this tank requires maintenance in four of the main maintenance types (vehicle, optical and optronical equipment, weapon, radio equipment). Some features of the "Luchs" are described in Appendix C. Table 4.1 summarizes the numbers of "Luchs" workorders available in the database (next page).

Year	# Workorders	# Maintenance Facilities	# Workorders Corrective Maintenance	# Workorders Scheduled Maintenance
1997	5150	37	2621	1786
1998	3571	40	1884	1469
1999	4254	41	2186	1682
2000	2888	47	1299	1245

Table 4.1 Summary of "Luchs" Workorders. *The sums of the numbers in columns 4 and 5 do not equal the total number of workorders in each year because there are more types of workorders present in the database, namely workorders for technical inspections and for technical modifications. Furthermore, some records were discarded due to insufficient data quality. Details are described in Chapter VII.*

It is essential for the simulation of a maintenance system or process to generate simulated failures of weapon systems and to model the subsequent repair process. In the simulation part of their study "System for Analysis of Maintenance" (SAM-Div), the Dornier company generates both scheduled maintenance events and failures due to enemy action and to wear and tear [Ref. 3]. SAM-Div also simulates the entire repair process from failure classification, vehicle recovery, and transport to the actual repair in the different maintenance types. The quality of the parameters used in this stochastic simulation determines the quality of the results, which are obtained through the simulation's outcome analysis. This and the following chapters investigate the question: Which of the parameters of SAM-Div can be derived from existing maintenance history data?

B. REPAIRTIME DISTRIBUTIONS

This section visualizes the repairtime distributions extracted from the data. Weibull distributions are fitted to the repairtimes for different maintenance types. Kolmogorov-Smirnov goodness-of-fit tests are used to check the quality of the Weibull model. The results of generalized likelihood-ratio tests defend the use of a Weibull model against the use of an exponential distribution.

The generation of repairtimes is a key factor in simulating the repair process of failed equipment. Most publications assume that the repair times are exponentially distributed (for instance, see [Ref. 5 and 6]). SAM-Div classifies the required maintenance actions into 11 categories, ranging from scheduled maintenance to catastrophic failure. For those categories requiring repair, SAM-Div assumes a triangular distribution of repairtimes around a mean. This mean is specific for each kind of equipment and for each maintenance type. The mean value is obtained from the MEZ-Katalog [Ref. 15] mentioned in Chapter I. The triangular distribution ranges from 1-24 maintenance man-hours (mhrs) for Organizational Maintenance and from 12-120 mhrs for Intermediate Maintenance [Ref. 3]. The new German Army structure will allow only very time limited maintenance actions within the Organizational Maintenance. Repairs will generally occur within the Intermediate Maintenance. Hence, the repairtime distributions extracted from the maintenance history data do not discriminate between Organizational and Intermediate Maintenance.

Generally, the active repairtime for a workorder can be retrieved from the Hx1-record in two ways: either from a datafield containing the sum of all actual repairtimes for this workorder, or from another datafield containing the sum of all standard repairtimes. The technicians inspecting the failed equipment extract these standard repairtimes from technical manuals or estimate them from their experience (in the case that the specific work is not listed). At first glance, the sum of the actual repairtimes seems preferable. However, a more in-depth consideration of this issue shows that these sums are highly correlated; about 84 percent of the Luchs workorders for corrective maintenance show exactly the same number for the actual repairtime and the standard repairtime. Differences between the actual repairtimes occur almost exclusively in one of two ways: either the entry for the actual repairtime is "zero" (which leads to the sum of the actual repairtimes being too low) or the entry for the actual repairtime is slightly higher than the entry for the standard repairtime. Although the latter case indicates a correct entry of the actual active repairtime, the generally very small deviation from the standard repairtime (in only about four percent of the records) will not make a material difference in the outcome of the analysis. The first case indicates that the actual repairtime was not entered after completing the maintenance action; the fraction of records of this kind is about 12 percent. Therefore, the sum of the standard repairtimes seems to be a more reliable estimator of the true sum of active repairtimes. More details on this issue are discussed in Chapter VII. As a result of these findings, "repairtime" in the analysis means "standard repairtime," unless otherwise stated.

Since SAM-Div simulates failures in all the different maintenance types of a weapon system or piece of equipment, the repairtime distributions are analyzed in the different maintenance types as well. Every equipment type or weapon system has a maintenance demand for its parts characterized by maintenance types. Table 4.2 shows a sample of some main maintenance types, identified by capital letters, and their meaning. A complete list of maintenance types can be found in [Ref. 15].

Maintenance Type	Meaning
A	electrical technology
B	hydraulic technology
C	optical technology
D	electronic technology
K	tank technology
M	radio technology
R	vehicle technology
W	weapon technology

Table 4.2 Main Maintenance Types (Sample).

Queries within the database software were used to create tables containing the repairtimes. These tables were exported into the statistical software package “S-Plus” for further analysis [Ref. 23]. Subsections 1 to 4 show the repairtime distributions for the main maintenance types of the “Luchs.” All times are measured in time units called “AW.” One AW is the equivalent of six minutes, so that 10 AWs constitute one man-hour of work. Section C analyzes the times associated with scheduled maintenance.

1. Vehicle (Maintenance Type R)

About 58 percent of the “Luchs” workorders for corrective maintenance in the time period investigated belong in this category. Figure 4.1 (next page) shows the histogram obtained for this maintenance type.

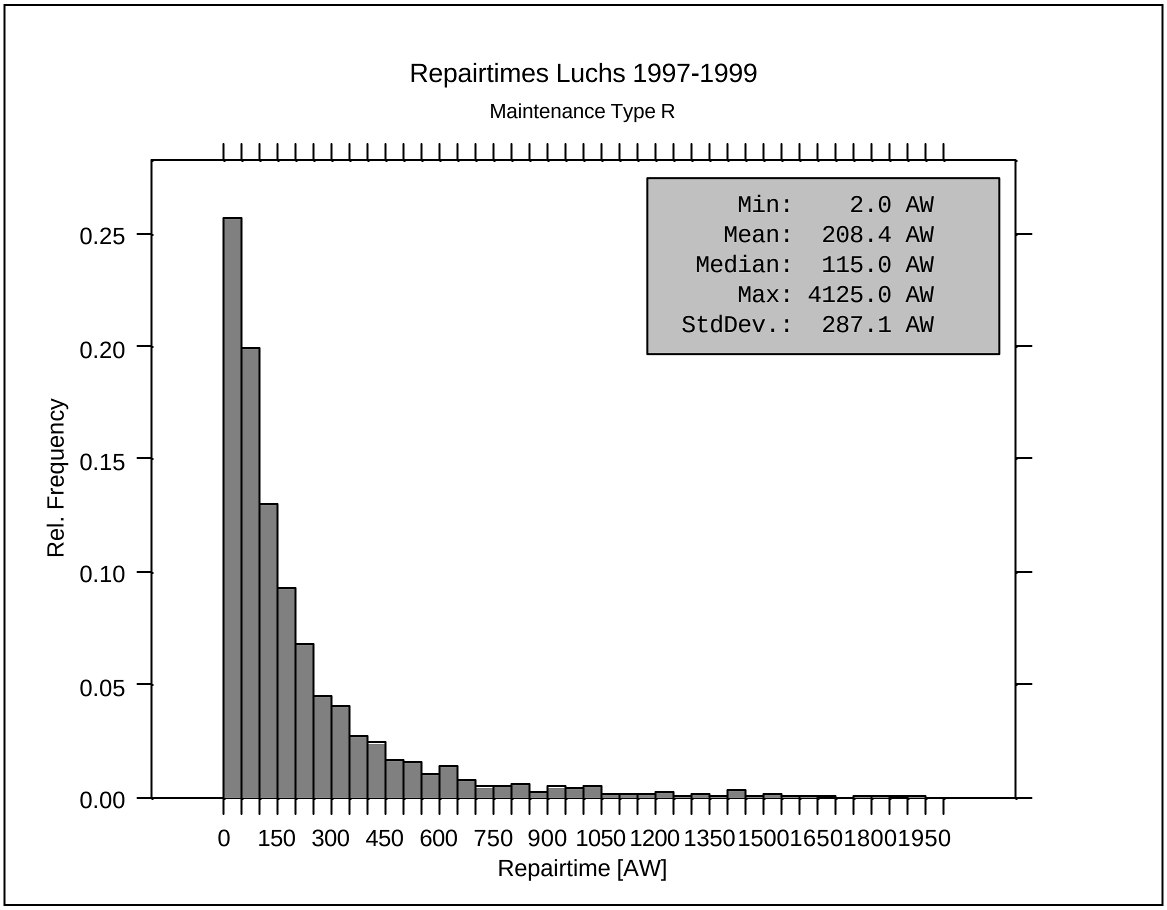

Figure 4.1 Histogram of Luchs Repairtimes (Vehicle). *There are 10 workorders with repairtimes > 2000 AW and 84 workorders with repairtimes > 1069 AW (which represents mean + 3*SD) within this data set. These repairtimes are extraordinarily long, which could indicate that the workorders are incorrect and should be excluded from the analysis. However, a careful examination of each of these workorders showed that extensive and complex work resulted in these outliers. All of these workorders should have been shifted to the Depot Maintenance level. Limited budgets for Depot Maintenance in recent years might be a reason for performing these repairs at the Intermediate Maintenance level.*

The histogram shown in Figure 4.1 suggests that an exponential distribution might be a better choice for simulating repairtimes than a triangular distribution. A more general model for the distribution of repairtimes uses the Weibull distribution [Ref. 16] with its parameters α (shape) and β (scale). The exponential distribution is a special case of the Weibull distribution, with shape parameter $\alpha = 1.0$. A Random Variable X is said to have a Weibull distribution with parameters α and β ($\alpha > 0$, $\beta > 0$), if the Cumulative Density Function (cdf) of X is

$$F(x; \alpha, \beta) = \begin{cases} 0 & x < 0 \\ 1 - e^{-(x/\beta)^{\alpha}} & x \geq 0 \end{cases} \qquad \text{[Ref. 16]}$$

Weibull distributions are widely used to model the factor "time" in reliability theory. The two parameters allow fitting the model to a wide variety of shapes. Therefore, Weibull distributions tend to have a better fit than single-parameter distributions, especially in the tail. More details on the Weibull distribution can be found in [Ref. 16] and in [Ref. 22]. In addition, [Ref. 22] gives an algorithm for how to generate random variables from a Weibull distribution.

Maximum Likelihood Estimation (MLE) can be used to fit a Weibull model to a given set of data [Ref. 16]. The details of this procedure are described in [Ref. 17]. The standard errors (SE) of the maximum likelihood estimates can be calculated from the estimated covariance matrix of the MLEs. Details can be found in [Ref. 17] as well.

In case of the repairtimes shown in Figure 4.1, the MLE-parameters for a Weibull distribution fitted to the data are the following:

$\alpha = 0.862$ SE(α) = 0.0098 Bootstrap SE(α) = 0.0110

$\beta = 191.30$ SE(β) = 1.9795 Bootstrap SE(β) = 3.8010

The S-Plus code, which produced these estimates, is shown in Appendix D. The Bootstrap estimates of the standard errors were obtained by resampling the repairtimes [Ref. 20].

Hypothesis tests can be performed to check the quality of the Weibull model and to validate it with the repairtimes from the year 2000. The Kolmogorov-Smirnov goodness-of-fit test is used in both cases to test whether the empirical distribution of a set of observations is consistent with a random sample drawn from a Weibull distribution with the estimated parameters [Ref. 16]. The test is available within S-Plus. The hypotheses for the first test can be stated as:

H_0: *The repairtimes of the Luchs 2000 data in maintenance type R come from a Weibull distribution with the estimated parameters*

H_1: *True cdf is not the Weibull distribution with the specified parameters*

This test, with a sample size of 100 from the 3,913 repairtimes, results in a p-value of 0.7021, which means that H_0 cannot be rejected. Hence, the Weibull model with the specified parameters is a reasonable model for the repairtime distribution.

The hypotheses for the validation test can be stated as:

H_0: *The repairtimes of the Luchs 2000 data in maintenance type R come from a Weibull distribution with the estimated parameters*

H_1: *True cdf is not the Weibull distribution with the specified parameters*

The test results in a p-value of 0.0007, which means that H_0 must be rejected at any reasonable level of significance. A closer look at the year 2000 repairtimes revealed that their distribution has a much heavier tail than the distribution shown in Figure 4.1. The fraction of repairtimes greater than 1000 AW in the year 2000 data is 12.3 percent compared to 2.6 percent in the 1997-99 data. As a result of this finding, every single year 2000 record with a repairtime greater than 1000 AW was investigated. Out of 82 such records, 30 were found to be collective workorders, which did not represent repairtimes related to a failure of a single vehicle. Therefore, these 30 records were deleted from the database. The Kolmogorov-Smirnov goodness-of-fit test was repeated and resulted in a p-value of 0.0605, which means that H_0 is accepted at a 5 percent level. A Weibull distribution with the specified parameters is a reasonable model for the year 2000 Luchs repairtime distribution in maintenance type R. More collective workorders with repairtimes less than 1000 AW are likely, so the p-value could probably be further improved by eliminating those records as well. The large sample size of 637 repairtimes in the year 2000 data might be another reason for the small p-value. W.J. Conover states in his book *Practical Nonparametric Statistics* [Ref. 18]:

> *We would be remiss if we did not point out that almost any goodness-of-fit test will result in rejection of the null hypothesis if the number of observations is very large. In other words, real data never really are distributed according to any known distribution.*

This citation illustrates the distinction between "statistical significance" and "practical significance" quite nicely. Sophisticated and powerful statistical tests can detect the smallest deviations of real data from a theoretical distribution. The question then is whether the deviations are large enough to be "practically significant." The answer to this question often depends on the context and the purpose of the application. In this case, the repairtimes are measured in AWs, i.e., in discrete numbers. This means that the repairtimes cannot be exactly Weibull distributed in a statistical sense because the Weibull distribution is continuous.

Figure 4.2 shows the histogram obtained for maintenance type R (2000).

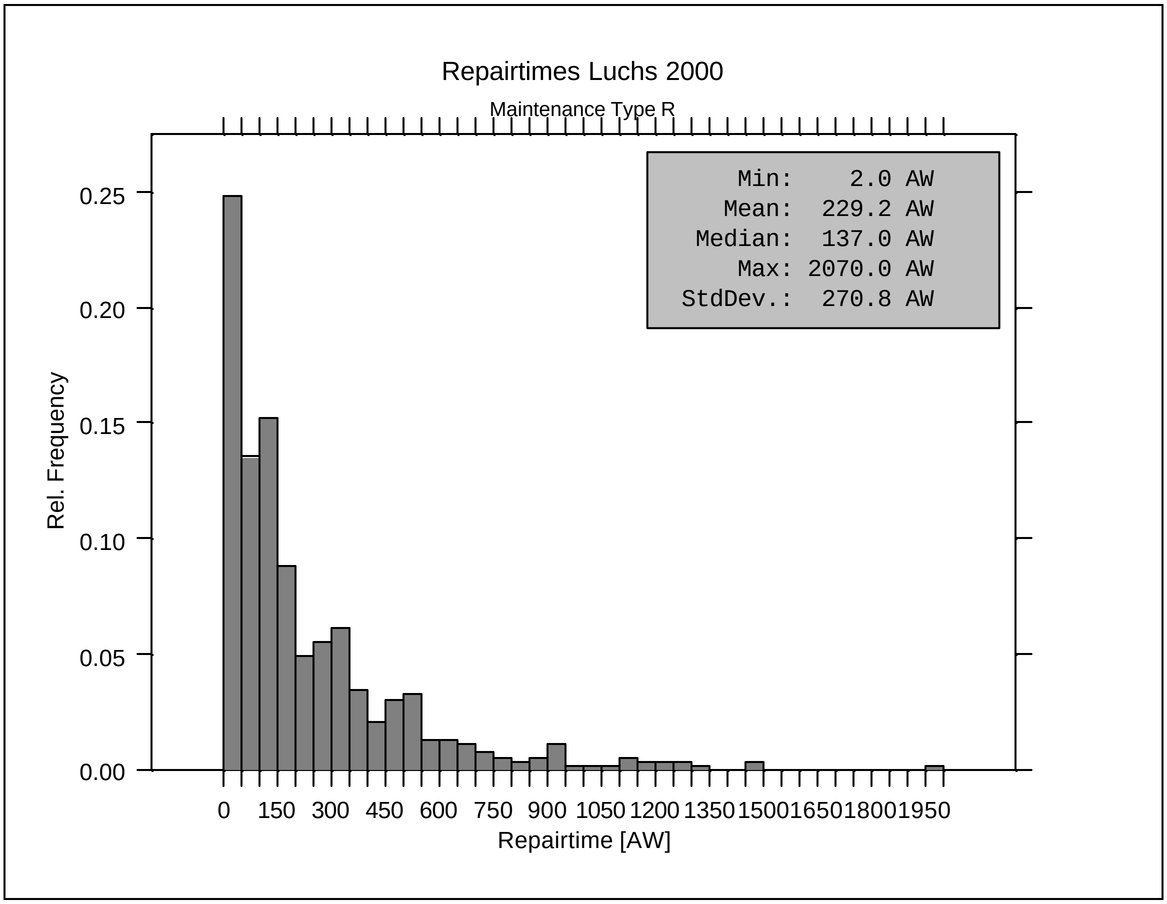

Figure 4.2 Histogram of Luchs Repairtimes (Vehicle) from 2000. *The histogram does not look as smooth as in Figure 4.1 because the number of bars (40) is quite high for the total number of observations (637). However, using the same number of bars in both figures simplifies comparisons between the two histograms. Figure 4.2 is based on the reduced dataset (after removal of 30 collective workorders).*

Figure 4.3 compares the distribution of the year 2000 data in maintenance type R with the theoretical distribution, which was obtained by fitting a Weibull model to the 1997-99 data.

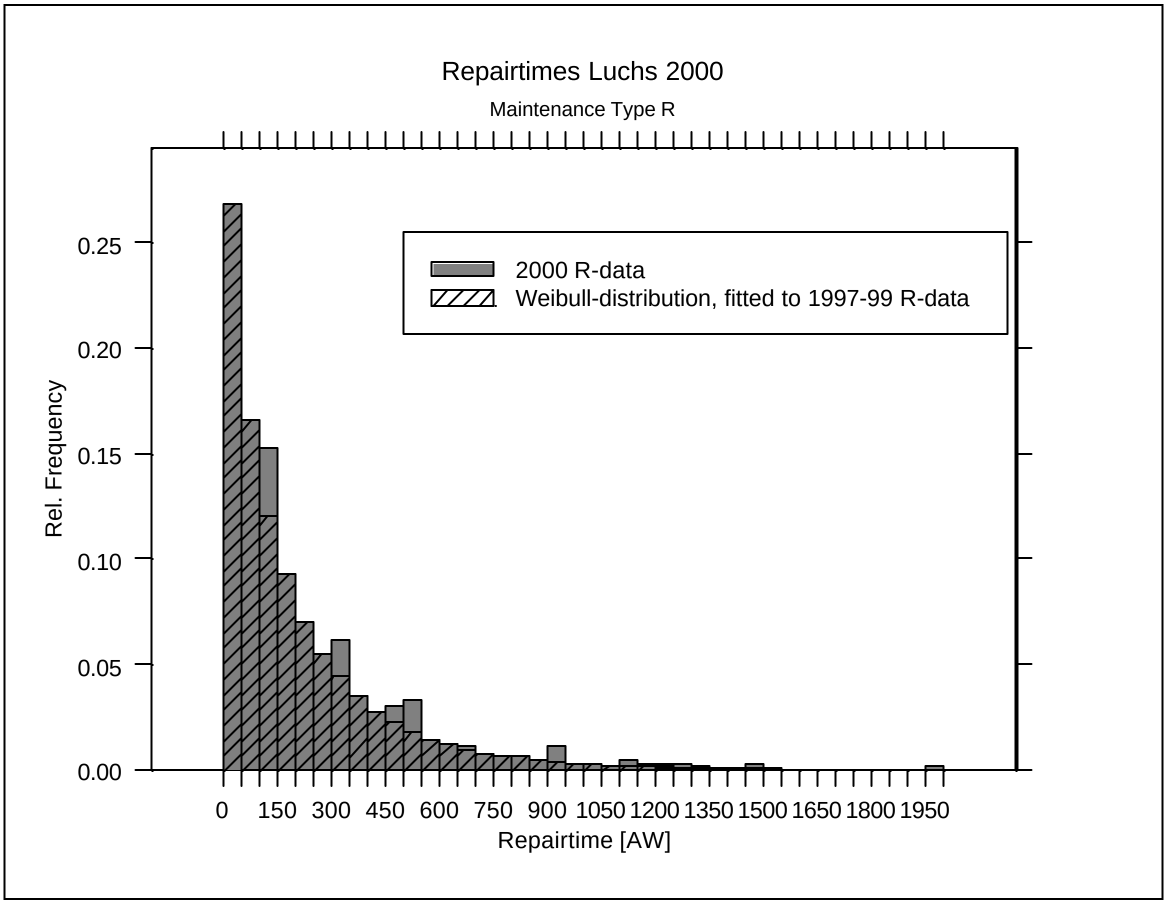

Figure 4.3 Comparison between Actual Data and Fitted Weibull Distribution. *The histogram shown in Figure 4.2 was supplemented with the histogram bars obtained by generating 100,000 numbers from the Weibull distribution fitted to the 1997-99 data. The optical impression of a good fit supports the conclusion of the Kolmogorov-Smirnov goodness-of-fit test.*

2. Weapon (Maintenance Type W)

About 31 percent of the "Luchs" workorders for corrective maintenance in the time period investigated belong into this category. Figure 4.4 shows the histogram obtained for this maintenance type (1997-1999).

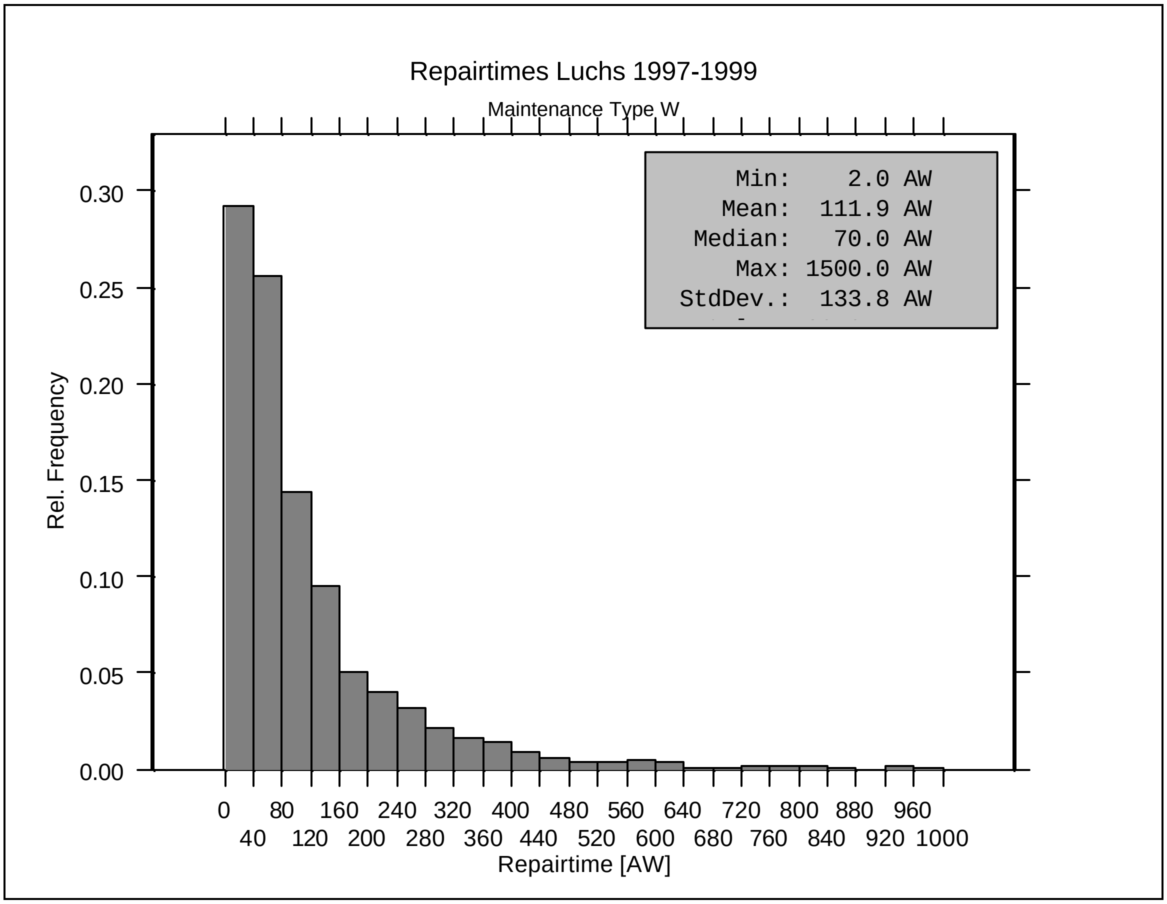

Figure 4.4 Histogram of Luchs Repairtimes (Weapon). *The shape of the distribution is quite similar to the previous ones. Again, a Weibull distribution seems a reasonable approach to model the repairtimes.*

The maximum likelihood estimates together with their standard errors for the Weibull model are:

$\alpha = 0.947$ SE(α) = 0.0149   Bootstrap SE(α) = 0.0179

$\beta = 112.33$ SE(β) = 1.5238   Bootstrap SE(β) = 2.7877

The Kolmogorov-Smirnov goodness-of-fit test with the hypotheses

H_0: *The repairtimes of the Luchs 2000 data in maintenance type W come from a Weibull distribution with the estimated parameters*

H_1: *True cdf is not the Weibull distribution with the specified parameters*

results in a p-value of 0.0095 after eliminating 13 collective workorders from the analysis. This means that H_0 must be rejected. The estimate of the shape parameter is close to 1.0; therefore, an exponential distribution might be another reasonable choice in this case. The one-sample Kolmogorov-Smirnov Test with hypothesized exponential distribution with mean 111.9 AW results in a p-value of 0.0386, a value still in the rejection region for a 5 percent-level test. On the other hand, if a random sample of 50 out of all year 2000 weapon-repairtimes is taken (with replacement), the same test yields a p-value of 0.4004. This means that the sample could have come from the specified exponential distribution. However, this p-value depends on the specific sample. Different samples yield different p-values. Therefore, the test was repeated a hundred times with different samples of size 50. The average p-value was 0.4038 with standard error 0.0281. A comparable average p-value of 0.4065 and standard error 0.0284 is the outcome of the same procedure with the Weibull model estimated above. Both distributions seem to be suitable models for the distribution of Luchs repairtimes in maintenance type W. This conclusion is further supported by Figure 4.5, which shows a similar shape and comparable summary statistics.

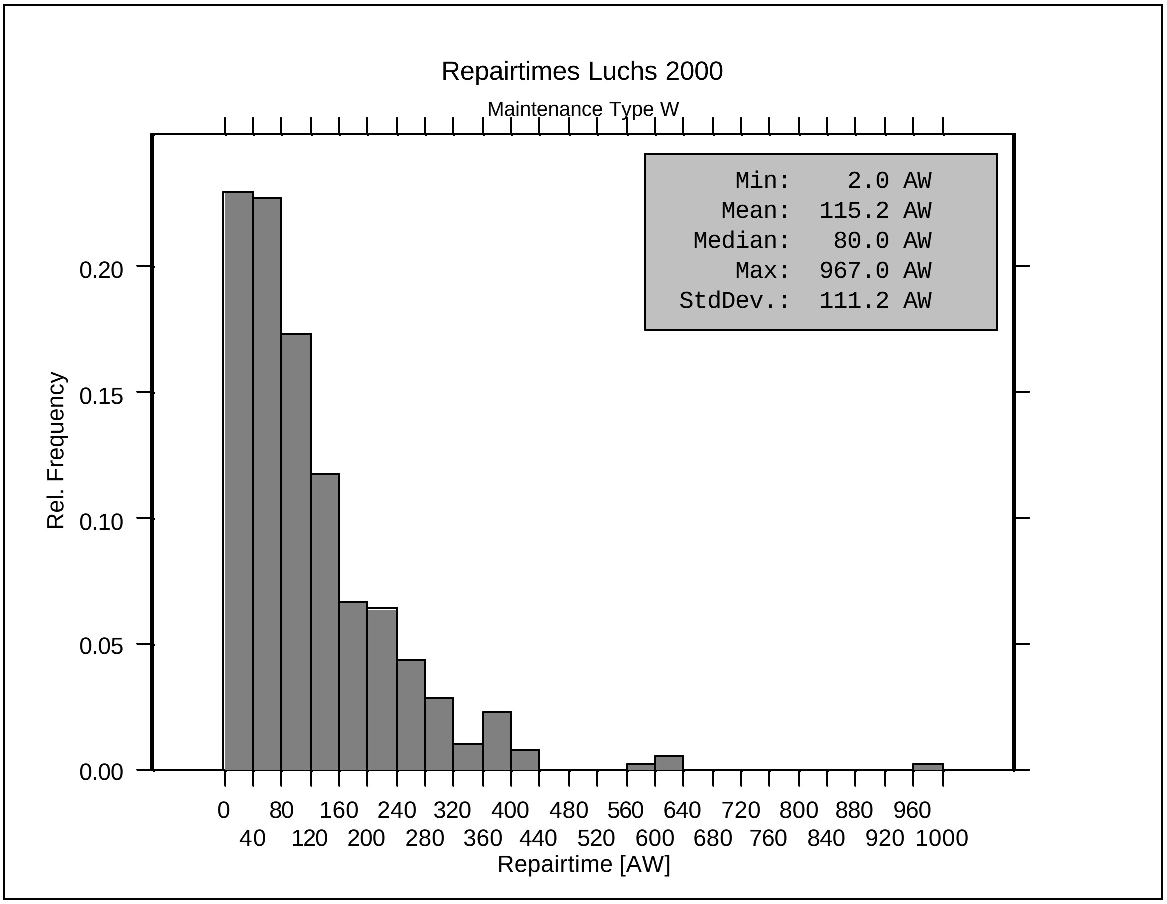

Figure 4.5 Histogram of Luchs Repairtimes (Weapon).

Figure 4.6 shows a slight lack of fit, especially in the leftmost bar of the histogram. Together with the smaller deviations in the other bars, this contributes to the rejection of the null hypothesis in the goodness-of-fit test.

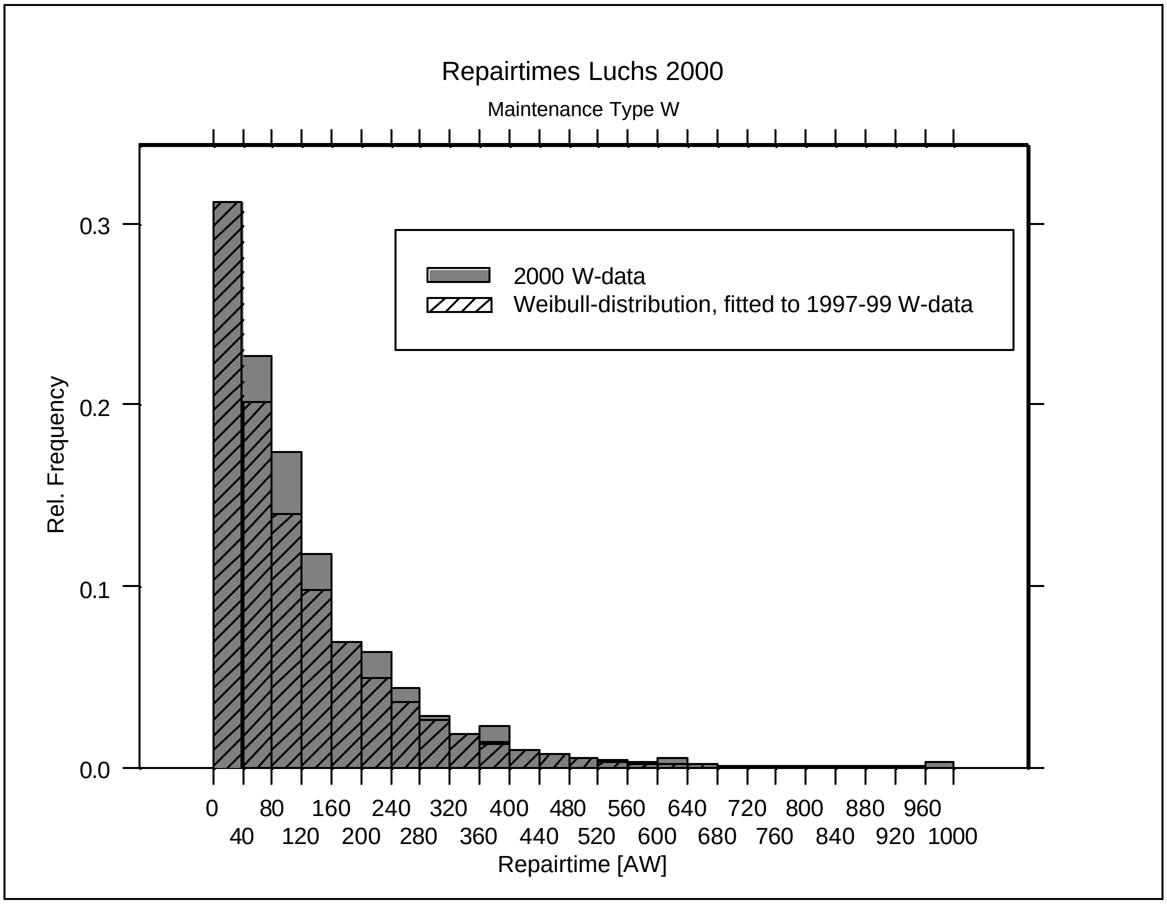

Figure 4.6 Comparison between Actual Data and Fitted Weibull Distribution.

The Weibull estimate of $\alpha = 0.947$ is close to an exponential distribution ($\alpha = 1$). Therefore, a generalized likelihood-ratio test (GLR) [Ref. 19] was performed to test the null-hypothesis that the data come from an exponential distribution against the alternative that the data come from a Weibull distribution. The p-value of this test is 0.000791, which means that the null-hypothesis must be rejected.

3. Radio Equipment (Maintenance Type M)

About 10 percent of the "Luchs" workorders for corrective maintenance in the time period investigated belong in this category. Figure 4.7 shows the histogram obtained for this maintenance type (1997-1999).

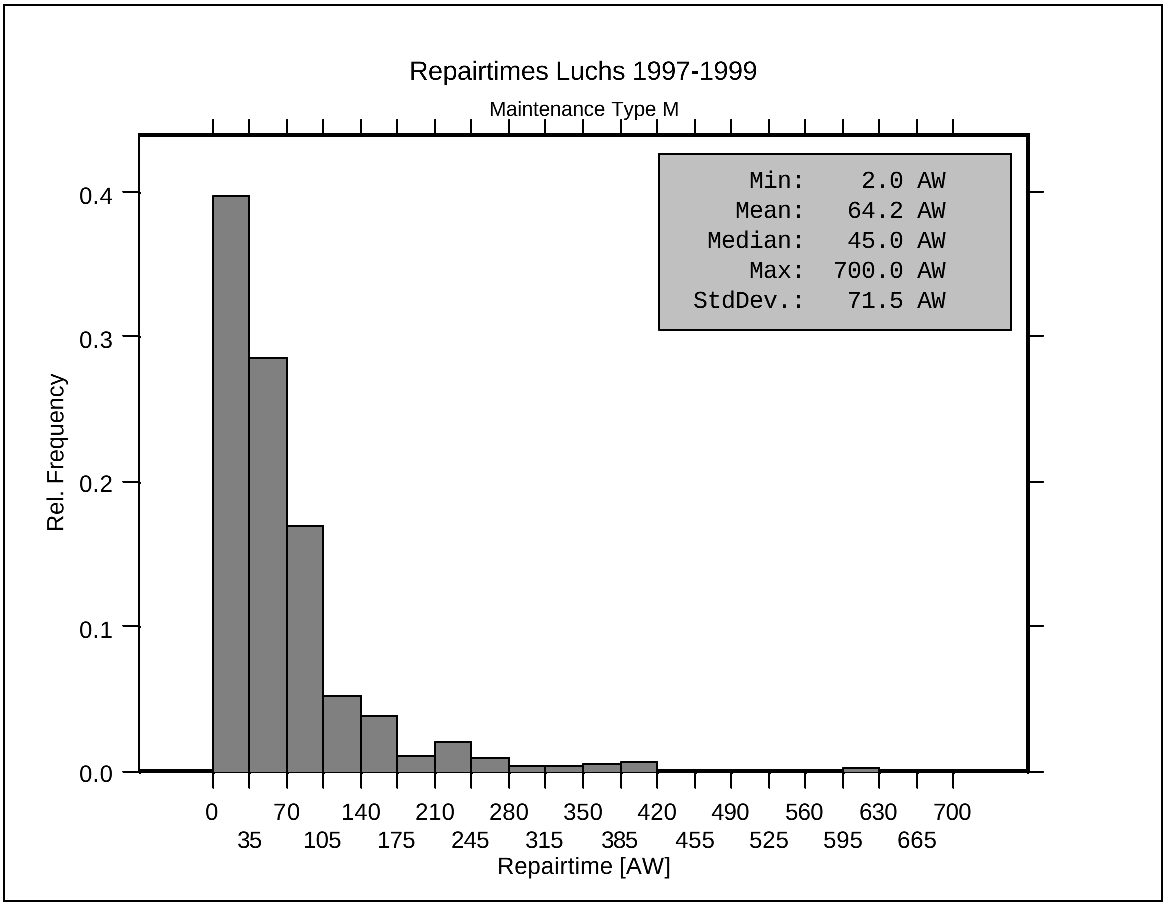

Figure 4.7 Histogram of Luchs Repairtimes (Radio Equipment).

Again, the shape of the distribution suggests fitting a Weibull model to the data. The maximum likelihood estimates together with their standard errors are:

$\alpha = 1.072$ $\quad$ $SE(\alpha) = 0.0291$ $\quad$ Bootstrap $SE(\alpha) = 0.0367$

$\beta = 66.24$ $\quad$ $SE(\beta) = 1.4527$ $\quad$ Bootstrap $SE(\beta) = 2.5729$

The Kolmogorov-Smirnov goodness-of-fit test with the hypotheses

H_0: *The repairtimes of the Luchs 2000 data in maintenance type W come from a Weibull distribution with the estimated parameters*

H_1: *True cdf is not the Weibull distribution with the specified parameters*

results in a p-value of 0.0013, so that H_0 is rejected at a 5 percent level. Although the fit of the Weibull model to the year 2000 data is not very good, the Kolmogorov-Smirnov goodness-of-fit test with sample size of 50 and 100 repetitions yields an average p-value of 0.1132 with a standard error 0.0133. Figure 4.8 reveals some slight differences in the shape of the distribution for the year 2000 data compared to those of 1997-99.

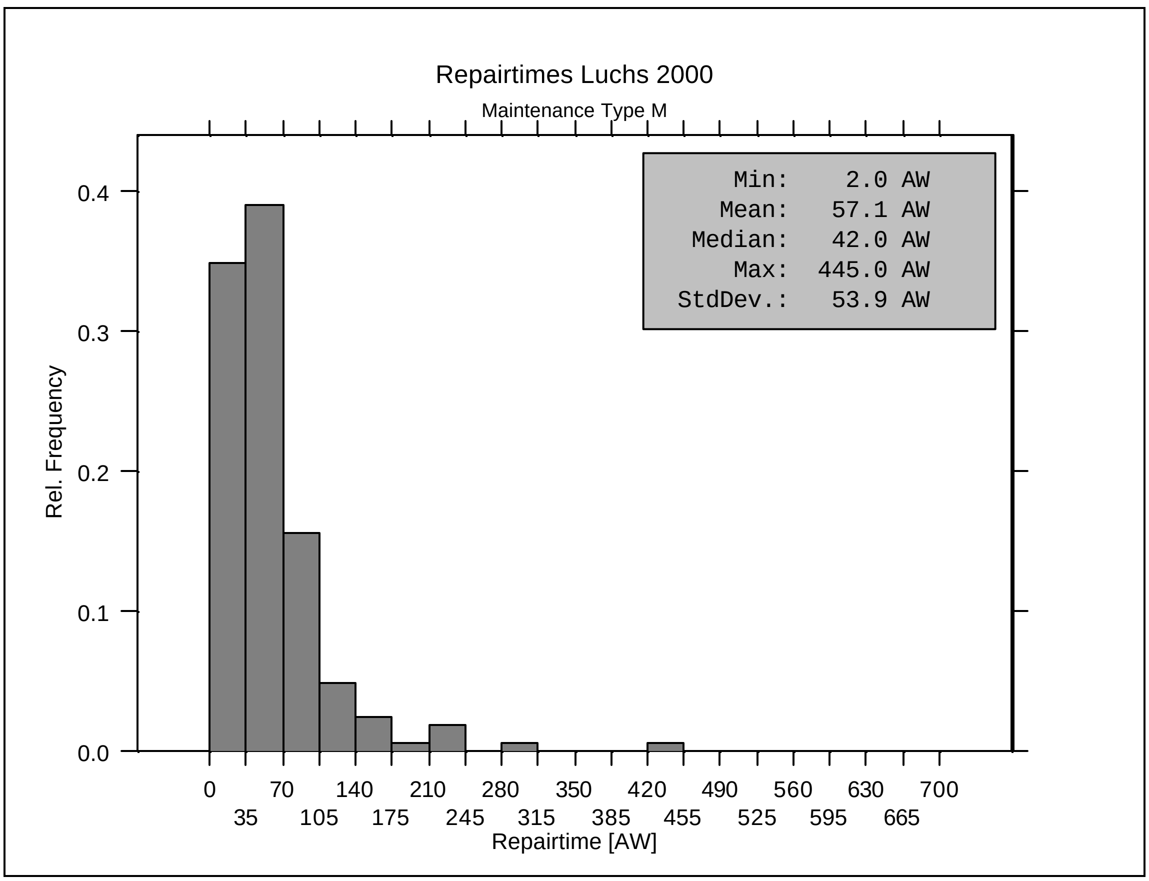

Figure 4.8 Histogram of Luchs Repairtimes (Radio Equipment).

Figure 4.9 compares the year 2000 data in maintenance type M with the Weibull-model fitted to the 1997-99 data. It confirms a slight lack of fit in the first two bars of the histogram. However, there are only 167 values in the year 2000 dataset in this maintenance type. Furthermore, the repair procedure for maintenance type M includes the search for the cause of an error or a failure, which is not the case in types R and W. This leads to larger variation within the smaller repairtimes because the experience of the repair specialist plays a major role. A more experienced technician usually needs much less time to find an error than a person with less experience.

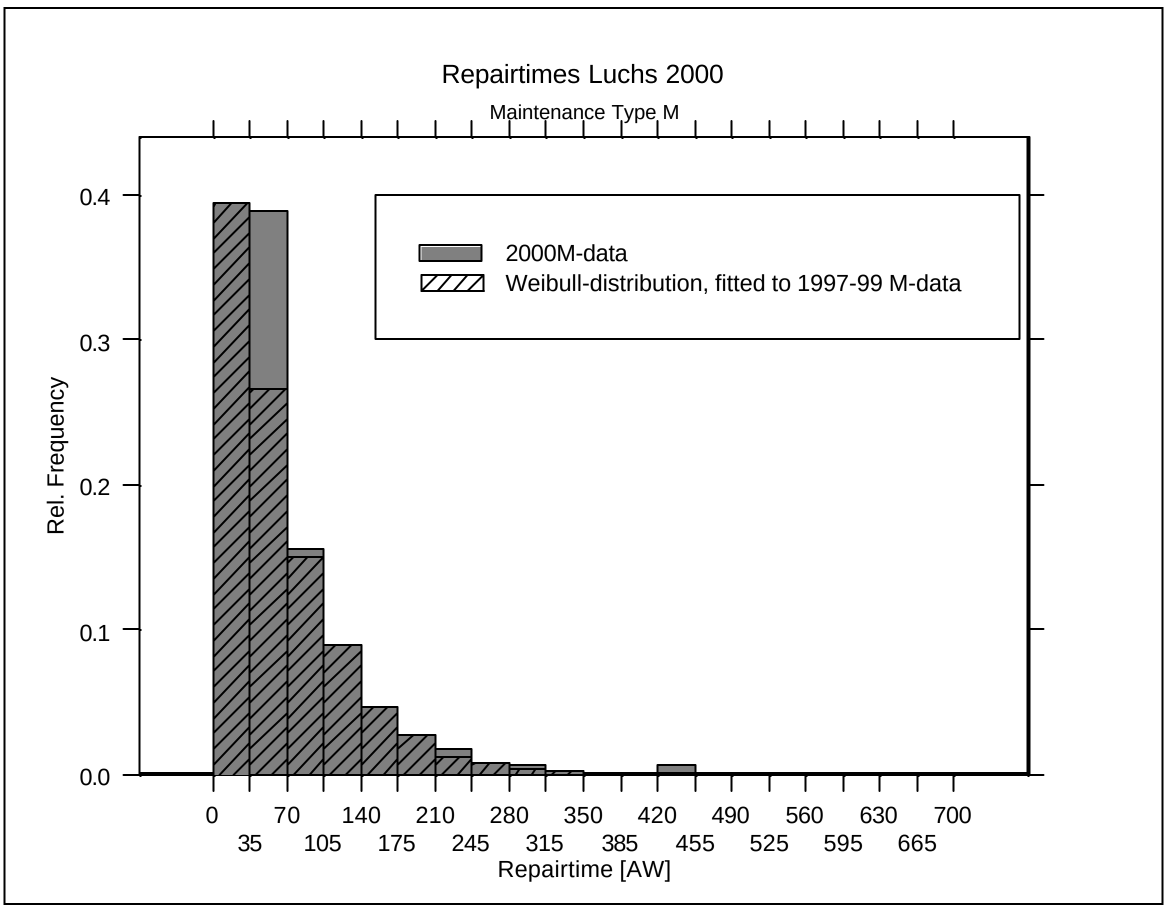

Figure 4.9 Comparison between Actual Data and Fitted Weibull Distribution.

The GLR p-value in this case is 0.01528, which means that the Weibull model is favorable against the alternative of an exponential distribution.

4. Optical and Optronical Equipment (Maintenance Type C)

Only about 0.3 percent of all workorders in the time period analyzed fall into this category, a fraction surprisingly small in view of the sophisticated night-vision equipment of the Luchs. Figure 4.10 shows the distribution of the repairtimes for this maintenance type.

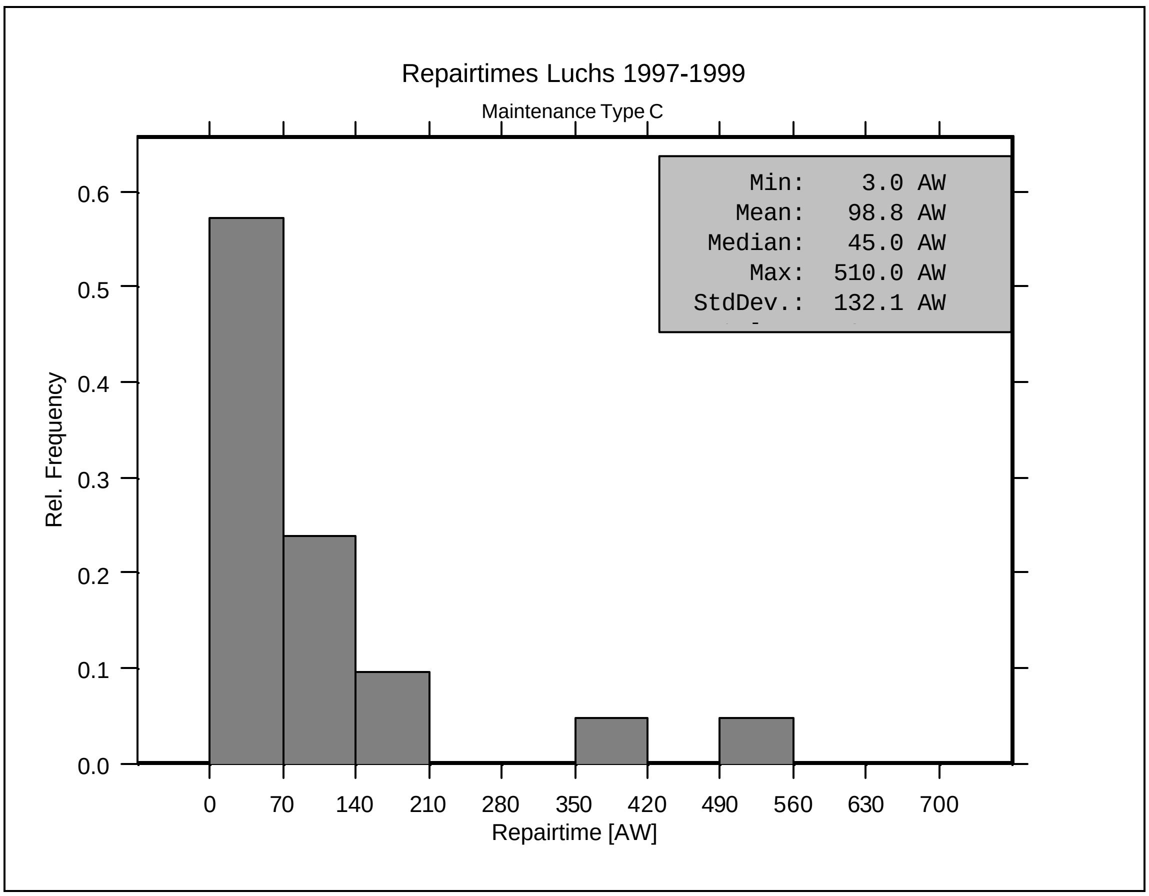

Figure 4.10 Histogram of Luchs Repairtimes (Optical Equipment).

Although only 22 workorders of this maintenance type are present in the database (21 from 1997-99, one from 2000), the histogram in Figure 4.10 indicates a shape similar to those in the other maintenance types. The maximum likelihood estimates of a Weibull model fitted to the data together with their standard errors are:

$\alpha = 0.843$ $\quad SE(\alpha) = 0.1321$ $\quad$ Bootstrap $SE(\alpha) = 0.1612$

$\beta = 89.40$ $\quad SE(\beta) = 12.8113$ $\quad$ Bootstrap $SE(\beta) = 25.0472$

The small sample size is reflected in relatively large standard errors of the estimates and a GLR p-value of 0.2721, which means that the data could have come from an exponential distribution as well. Figure 4.11 provides a visual impression of the goodness-of-fit of the Weibull model to the 1997-99 data.

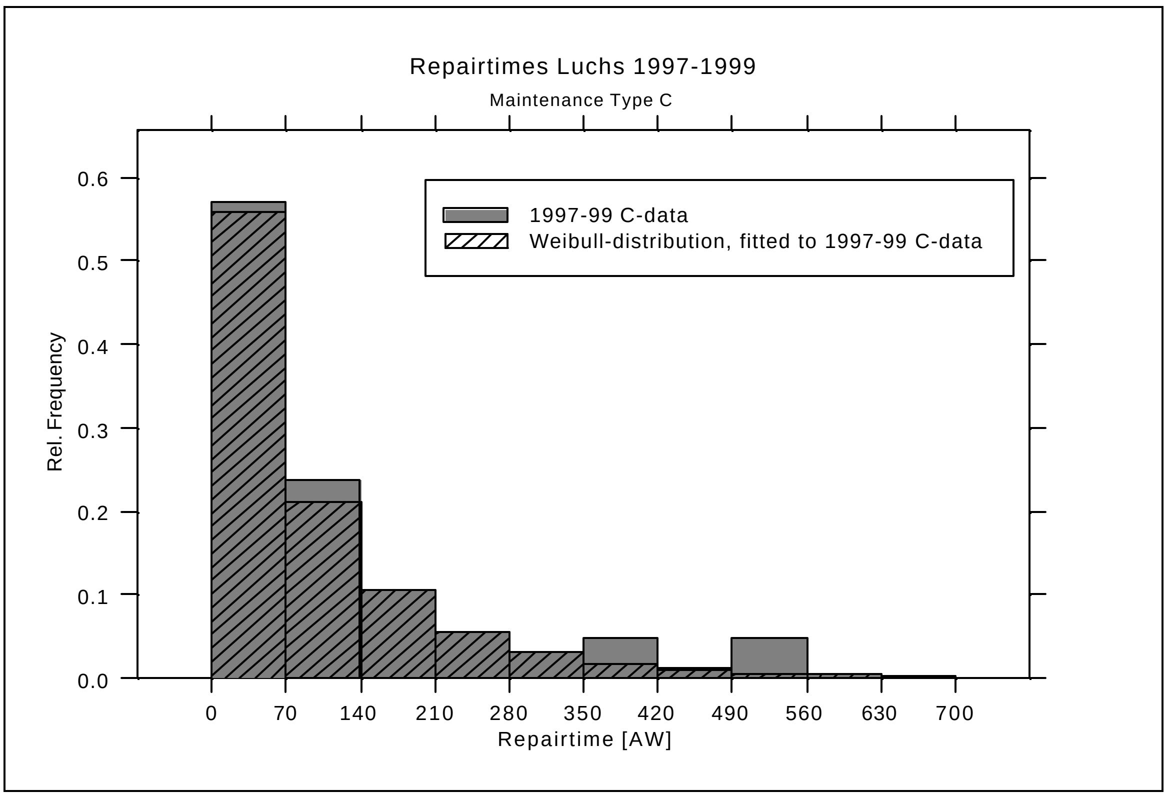

Figure 4.11 Comparison between Actual Data and Fitted Weibull Distribution.

C. SCHEDULED MAINTENANCE

Scheduled maintenance on the Luchs is done in all maintenance types and in both Organizational and Intermediate Maintenance. There are different kinds of scheduled maintenance activities, which differ in the amount and in the complexity of work. Some are scheduled on a timely basis, for example, every month, and some depend on other measurements, like the number of rounds fired. SAM-Div simulates scheduled maintenance on a time-driven basis with a mean number of activities (e.g., 12) per vehicle per year and a mean time per activity (e.g., 73 AW). These data are specific for every piece of equipment and are included in the simulation database. Missing "real" data are computed from the MEZ-Katalog, which is somewhat arbitrary because the analyst has to split the maintenance demand specified in this catalog into corrective and scheduled maintenance. Actually, the Luchs' demand for scheduled maintenance is completely determined by the regulations of the technical manuals. This, however, is not reflected in the workorder records analyzed in this study. The standard time for a certain scheduled maintenance activity, like a monthly inspection, should be a fixed amount of time. Of course, there will be some variation in the actual time needed to perform this task. The records, however, show a substantial variance in the standard times, depending on the maintenance facility and other factors. Table 4.3 illustrates the spread of the standard times for some scheduled maintenance activities (next page).

Activity	Minimum Standard Time [AW]	Maximum Standard Time [AW]
F1 Weapon	30	40
F1 Vehicle	30	40
F2 Weapon	40	110
F2 Vehicle	60	200
F3 Weapon	60	420
F3 Vehicle	200	760
F3 Radio	80	120
F4 Weapon	80	264
F4 Vehicle	400	1170

Table 4.3 Variations in Standard Times for Scheduled Maintenance Activities.
The scheduled maintenance activities listed above are performed after certain time intervals on a regular basis. For instance, F1 is performed monthly and represents a kind of thorough check. Higher activities are more complex and time consuming. They include all the activities with a smaller number, for example F3 includes F2 and F1.

One cause for the spread of these times is the fact that the activities listed above are sometimes combined with certain additional scheduled maintenance activities, for instance a special service after every 3,000 liters of fuel consumption. Normally, this is noted in the description of the work performed within the workorder record, but in some cases, one might have omitted or forgotten to enter this information. Another cause of the variation is the fact that sometimes certain activities are split between Organizational and Intermediate Maintenance. For instance, simpler, less time-consuming working positions of a F3 Vehicle-activity are sometimes done by the maintenance platoon of the vehicle's battalion (Organizational Maintenance), whereas the more complex and time-consuming work is performed in a maintenance unit

(Intermediate Maintenance). If a separate workorder is written in each maintenance facility, then two standard times appear in the database with possibly huge differences in value. As mentioned earlier, capacities of Organizational Maintenance will be reduced in the next German Army structure, thus shifting responsibilities toward Intermediate Maintenance. Therefore, the uncertainty associated with the split of some workorders should resolve in the near future. Hence, it seems more reasonable to determine the times needed for scheduled maintenance activities from the norms of the technical manuals and to assess the variability of these activities from workorder records after the maintenance system is restructured.

D. CONCLUSIONS

This chapter showed that the repairtime distributions of Luchs workorders differ substantially from the assumptions made in SAM-Div. The distributions can be modeled using a Weibull distribution with parameters depending on the maintenance type. The parameters were estimated using Maximum Likelihood Estimation and data from 1997 - 1999. In many cases, the MLE-parameters are quite close to an exponential distribution. Statistical tests, however, showed that the use of the Weibull distribution is more appropriate to model repairtimes. This parametric approach is a suitable way to generate repairtimes within a simulation of the repair system. Of course, the repairtimes generated from a Weibull distribution must be converted to integers because AWs are integer values. On the other hand, it seems inappropriate to model scheduled maintenance activities from the data currently available. Rather, the distributions of the times associated with these activities should be determined at a later point in time, as described in Section C.

V. SPARE PARTS

A. INTRODUCTION AND OVERVIEW

The availability of spare parts plays a decisive role in the repair process. This chapter analyzes the usage and the supply times of spare parts used in 1998 Luchs maintenance (Section B). Section C analyzes supply time distributions of 1998 Luchs workorders, whereas Section D compares the empirical distribution functions of these workorders.

The performance of any maintenance system depends on the effectiveness of the spare part supply. A repair cannot be executed until all needed spares are available. Due to operational and budgetary reasons, the amount and type of spare parts stocked within a maintenance facility is limited. For instance, a maintenance unit, which generally supports various kinds of equipment, cannot stock engines for all the different vehicles it supports. The stock within a maintenance facility is therefore limited to some individual or bulk expendable supplies, which are commonly used and generally not very expensive, e.g., screws or washers. Spare parts on the other hand are stocked and supplied by the supply corps. However, stockpiling the right items in the right amount at the right place is a very complex task from both a military and economic point of view. Stockpiles of more and more sophisticated spare parts are a major cost factor not only in military budgets. Airlines, manufacturing plants, etc. are faced with similar issues. In the last few decades, many of these organizations have managed to reduce their inventories and safety stocks without reducing their efficiency. Some examples cited in RAND's "Velocity Management" report include the Cummins Diesel plant, whose service part division reduced its average inventory on the floor from $173 million to $22 million. Detroit Diesel Remanufacturing has been able to reduce its safety stock from 30 days to 5 days by reengineering its operations [Ref. 1].

Naturally, the military is also highly interested in reducing their stockpiles, especially in spare parts, which seem to offer a huge potential for downsizing its budget. However, the circumstances for reducing military stockpiles are different from the commercial world. The demand for repairs and spare parts depends on the mission, the scenario, and many more, often unpredictable factors. As a result, the demand for spare parts varies greatly over time, which makes finding an appropriate level for the stock difficult. Nevertheless, the availability of spare parts in a timely manner is a precondition for successful maintenance and repair. Force readiness depends on the effectiveness of the maintenance and repair process. This means that an adequate supply of spare parts must be ensured, especially in missions outside the native country. Accurately predicting the demand for spare parts seems quite difficult, if not impossible. John B. Abell concluded his RAND study “Estimating Requirements for Aircraft Recoverable Spares and Depot Repair” with the remark, “We are impressed with the difficulty of the problem of spares requirements.” A realistic simulation of a maintenance system must take this problem into account.

The SAM-Div simulation assigns a supply time for spare parts to each repair. These supply times have triangular distributions with parameters adjustable for each kind of equipment and for each maintenance type. SAM-Div differentiates between items in standard supply, with supply times distributed between 0 and 42 hours, and critical items with supply times between 12 and 192 hours. Furthermore, SAM-Div in its current version can model the repair process for up to 10 major assemblies per equipment type.

Some questions arising from the issue of spare parts requirements are:

- What spare parts and major assemblies, and what quantities, are needed to repair certain types of equipment?
- What spare parts and what quantities are needed in the scheduled maintenance of a certain type of equipment?
- Which spare parts are "critical items" with long supply times?
- What do the supply time distributions look like?
- What is the probability that the supply time of a workorder exceeds a certain amount of time?

This chapter tries to answer these questions by analyzing maintenance history data, again illustrated with the "Luchs." Section B addresses the first three of these questions, whereas Sections C and D deal with the last two.

B. SPARE PARTS USAGE AND SUPPLY TIMES

This section addresses the first three questions posted above by extracting supply-related information from the Hx3-files. Supply times are calculated by subtracting the date at which a spare part was ordered from the date it became available. Thus, all supply times are in whole days and not in hours as in SAM-Div. The tables shown in the following subsections were created using Microsoft Access. It is emphasized that the underlying data are not complete (Chapter III). Hence, the column *Amount* contained in the table represents a lower bound on the true amount used of the particular item.

1. Corrective Maintenance

Table 5.1 shows a selection of spare parts used in corrective maintenance actions during 1998. The whole list consists of 1,707 items and is grouped by stock numbers.

Luchs 1998	Corrective Maintenance			SupplyTime [days]			
Stock Number	**Item**	**Amount**	**Count**	**Avg**	**StDev**	**Max**	**Min**
2530123005149	RAD, LUFTREIFEN	111	63	35.1	38.7	113	1
2530123008903	RAD, LUFTREIFEN	82	51	62.2	61.7	172	1
5330121619019	DICHTUNG,RADIAL-	76	24	12.0	11.1	39	1
6650121719741	PERISKOP, GEPANZERT	75	40	10.8	8.4	44	2
5310121848509	SCHEIBE, UNTERLEG-	72	14	14.1	8.7	29	1
5306121628456	SCHRAUBE, VIERKANTA	70	16	8.8	5.7	21	1
3110121632863	LAGER,ROLLEN-,NA	68	22	15.2	16.8	80	1
5330121597608	DICHTUNG,GUMMISP	63	35	19.1	17.8	60	1
5330121704128	DICHTPACKUNG MIT	56	21	7.7	6.7	24	0
5330121633798	DICHTPACKUNG,VOR	53	22	6.8	5.1	19	0
5330121633797	DICHTUNG,RADIAL-	48	14	18.0	14.3	39	3
4730121644614	ADAPTER,GERADE,R	44	10	43.8	23.7	96	13
2540121879752	POLSTER SITZ FZG	44	32	16.7	21.5	81	1
5330121635123	DICHTUNG,RADIAL-	41	18	7.4	4.8	20	1
2540121597603	STOSZDAEMPFER,TE	40	22	27.9	38.5	131	0
5340121762773	RIEMEN, GURTGEWE	38	19	18.3	16.4	60	1
5365121937187	ABSTANDSHUELSE	35	6	59.8	42.0	106	15
2520121598366	WELLE,GETRIEBE	35	25	23.8	23.9	86	1

Table 5.1 Sample of Spare Part Usage 1998 (Corrective Maintenance). *The first two columns identify the spare part by stock number and item name. The third column specifies the amount of spare parts used during 1998, whereas the fourth column represents the number of orders containing the specified spare part. Columns 5 to 8 show some basic supply time statistics for each kind of spare part listed. This table was sorted in decreasing order of "Amount" and decreasing order of "Avg." Example: The first item listed above, a tire-wheel combination with stock number 2530-12-300-5149, was*

ordered 111 times within 63 distinct orders. The minimum supply time for a single item was 1 day, the maximum supply time 113 calendar days. The average supply time for this item was 35.1 days, the standard deviation in supply time was 38.7 days.

Reporting the median supply time instead of the average in tables like Table 5.1 would generally provide a better impression of the supply situation because the average is quite sensitive to outliers in the data. However, Access does not offer the choice to report medians. Figure 5.1 illustrates this situation for the tire-wheel combination listed as the first item in Table 5.1:

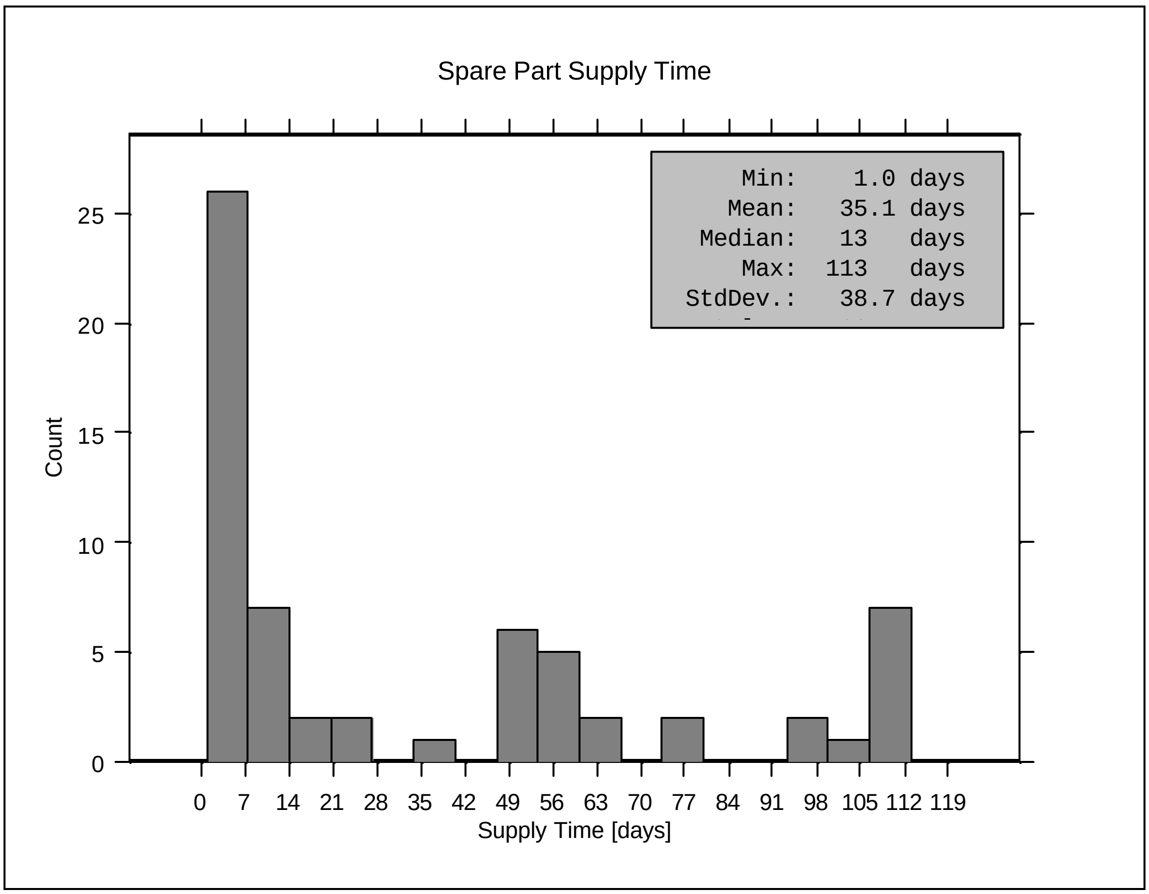

Figure 5.1 Distribution of Spare Part Supply Times for Stock Number 2530123005149. *This histogram shows how misleading an average in a skewed distribution can be. Although the average supply time for this item is 35.1 days, 50 percent of orders arrived within the median supply time of 13 days.*

Tables like Table 5.1 can be used to crosscheck stocking policies and general supply statistics against statistics for a particular weapon system. Even more importantly, these tables can be used to determine "critical items" in the supply chain. These are items, which are essential for the performance or safety of a piece of equipment, and, which show problems in resupply. The first criteria cannot be extracted from the table. It has to be evaluated by technical experts in combination with the tactical user of the weapon system. Problems in resupply, however, can be identified. Larger numbers in the supply time columns 5 to 8 indicate such problems, especially when the number of orders is also high. Currently, there is no firm definition of a critical item from a maintenance point of view.

The supply characteristics of a spare part could be summarized in a "critical index," which might be calculated from an expression involving some of the supply statistics listed in Table 5.1. This critical index should also be weighted by the relevance of an item for the performance or safety of the weapon system, as mentioned earlier. The items could then be sorted by their "critical index." Hence, a list with critical items could be established for further evaluation by experts. A suitable expression for an item's critical index could be:

$$\mathbf{CInd} = w * m^{2} * \mathbf{n} \qquad (5.1)$$

with: ω = relevance factor (between 0 and 10)

μ = average supply time

n = number of orders during a certain time period

The average supply time is squared to reduce bias toward the number of orders. The top of the list of critical items derived from the 1998 supply statistics using Formula 5.1 is shown in Table 5.2:

Luchs 1998	**Corrective Maintenance**					
Stock Number	**Item**	**Amount**	**Count**	**Avg** [days]	**Critical Index**	**Relevance Factor**
2530123008903	RAD, LUFTREIFEN	82	51	62.2	1579283	8
2530123005149	RAD, LUFTREIFEN	111	63	35.1	621888	8
6150121969839	KABEL, SPEZIAL-,	9	9	82.7	307520	5
2530121664699	STANGE STABILISI	17	10	87.4	229163	3
1005121909759	SITZ VOLLST	15	15	60.1	216480	4
3040121631526	HALTELAGER,ACHSE	30	23	29.5	160362	8
2520121598366	WELLE,GETRIEBE	35	25	23.8	142086	10
4320121649400	PUMPE,RADIALKOLB	26	17	33.9	117097	6
2920121601002	REGELGERAET 1 GE	32	28	27.3	104504	5
5820121792733	SE FUNK XK 240	4	4	49.3	97023	10
3030011793265	BELT,V	4	4	122.5	60025	1
2540121597603	STOSZDAEMPFER,TE	40	22	27.9	51241	3
1005121598118	GRIFFBAUGRUPPE, WAF	9	9	23.7	50410	10
2530121671285	LENKSTANGE	14	10	20.1	40401	10
2815123321466	MOTOR, DIESEL-	7	7	23.7	39366	10
6650121719741	PERISKOP, GEPANZERT	75	40	10.8	37325	8

Table 5.2 Partial List of Critical Items. *The relevance factors shown in Table 5.2 were arbitrarily chosen for demonstration purposes. The items are sorted according to their critical index, which was computed using Formula 5.1.*

The methodology presented here can identify weapon-system specific supply problems, which logisticians can then address.

2. Scheduled Maintenance

Scheduled maintenance activities are sometimes combined with smaller repairs. Table 5.3 shows a sample of the spare parts and expandable items used in connection with scheduled maintenance.

Luchs 1998	Scheduled Maintenance			SupplyTime	[days]		
Stock Number	**Item**	**Amount**	**Count**	**Avg**	**StDev**	**Max**	**Min**
5330121415114	O-RING	65	65	10.9	9.0	48	1
2910121643075	FILTER,DURCHFLUS	65	65	10.7	9.3	48	0
2910123035410	FILTEREINSATZSAT	57	57	14.6	15.0	88	1
2910121288594	FILTEREINSATZ, DURC	34	34	12.1	8.4	29	0
5310121455778	SCHEIBE SICH10,5	32	4	14.8	4.5	20	9
2940121563336	LUFTFILTER	31	13	8.9	8.4	26	1
4730121644557	ADAPTER,GERADE,R	21	20	41.8	38.4	97	2
5330123324652	DICHTUNG	20	12	3.2	1.7	6	1
5330121983635	DICHTUNG, NICHTM	17	3	12.7	5.5	18	7
2910121431087	TANKBEL!FTUNGSFILTER	16	4	16.3	17.3	42	5
6650121719741	PERISKOP, GEPANZERT	15	8	11.9	9.5	33	3
2910121643095	FILTEREINSATZ,DU	13	11	14.8	12.1	29	1
1055121420976	MUENDUNGSKAPPE	13	2	19.0	18.4	32	6
4330121521224	FILTEREINSATZ	12	12	17.0	7.3	25	7
5330123303427	DICHTUNG	12	9	8.7	3.2	12	5
5330121564852	DICHTUNG	10	6	15.5	2.3	20	13
5330121635122	DICHTUNGSBAUGRUP	10	3	6.7	0.6	7	6
3030011793265	BELT,V	9	9	61.8	52.4	124	3

Table 5.3 Sample of Spare Parts Usage 1998 (Scheduled Maintenance). *Table 5.3 was sorted in decreasing order of "Amount." Spare parts and expandable items for scheduled maintenance activities are ordered ahead of time. Therefore, the supply time statistics shown above can be viewed as non-critical.*

3. Major Assemblies

Information about major assemblies, which were exchanged during the repair of a piece of equipment, is contained in the Hx4-record of a workorder. This information includes both the serial number and mileage or operating hours of the defect assembly as well as those of the replacement assembly. Ideally, tracking this information can help one detect design flaws and identify "lemons." Furthermore, statements about mean time between failures (MTBF) for different kinds of major assemblies could be made. In addition, the question "Which major assemblies of a weapon system should be modeled in a simulation like SAM-Div?" could be addressed. However, the data quality of the Hx4-files is insufficient for these tasks. Table 5.4 lists all major assemblies of the Luchs, which are contained in the 1998 Hx4-file. Remarkably, all records come from only two maintenance facilities, whereas the Hx3-file lists 59 assemblies from 16 units.

Unit #	Work-order #	Stock Number	Major Assembly	Amount	Supply Time	Serial #
03594	9800528	2520123411311	ACHSE, FAHRZEUG, AN	1	2	134794
03594	9801232	2520121597949	ACHSE,KRAFTFAHRZ	1	1	188418
03594	9801232	2520121597949	ACHSE,KRAFTFAHRZ	1	1	189065
03594	9801431	1240121619548	EINBLICKBAUGRUPPE	1	1	5239
03594	9802016	2815123321466	MOTOR, DIESEL-	1	1	403999075092
03594	9803042	2520121597942	GETRIEBE,HYDRAUL	1	1	697
03594	9804344	2815123321466	MOTOR,DIESEL-	1	27	403999052325
03594	9804955	1005121538889	ABZUGSVORR	1	1	23991
03594	9806480	2520121597950	ACHSE,KRAFTFAHRZ	1	1	176298
31113	9801213	2590121597614	ZYLINDERBAUGRUPPE	1	14	3203

Table 5.4 Major Assemblies Luchs 1998. *The 1998 Hx4-file contains only 10 of the 59 records listed in the Hx3-file. For instance, only two engines are listed, whereas Table 5.2 contains seven engines. This shows that the data quality of the Hx4-file is insufficient to track major assemblies or to obtain performance data for simulations or other purposes.*

C. WORKORDER SUPPLY TIME DISTRIBUTIONS

The workorder supply time is defined as the time span between ordering the first spare part and having all the spare parts that are needed for the workorder available. The workorder supply time is therefore a major time factor in the repair process. That is, it can be used to model the spare parts supply in a simulation of the repair process. Modeling the workorder supply time has the benefit of not having to model the supply of each individual spare part within the repair process of a piece of equipment.

Figure 5.2, 5.3, and 5.4 show the 1998 supply time distributions for maintenance types R (vehicle), W (weapon), and M (radio equipment).

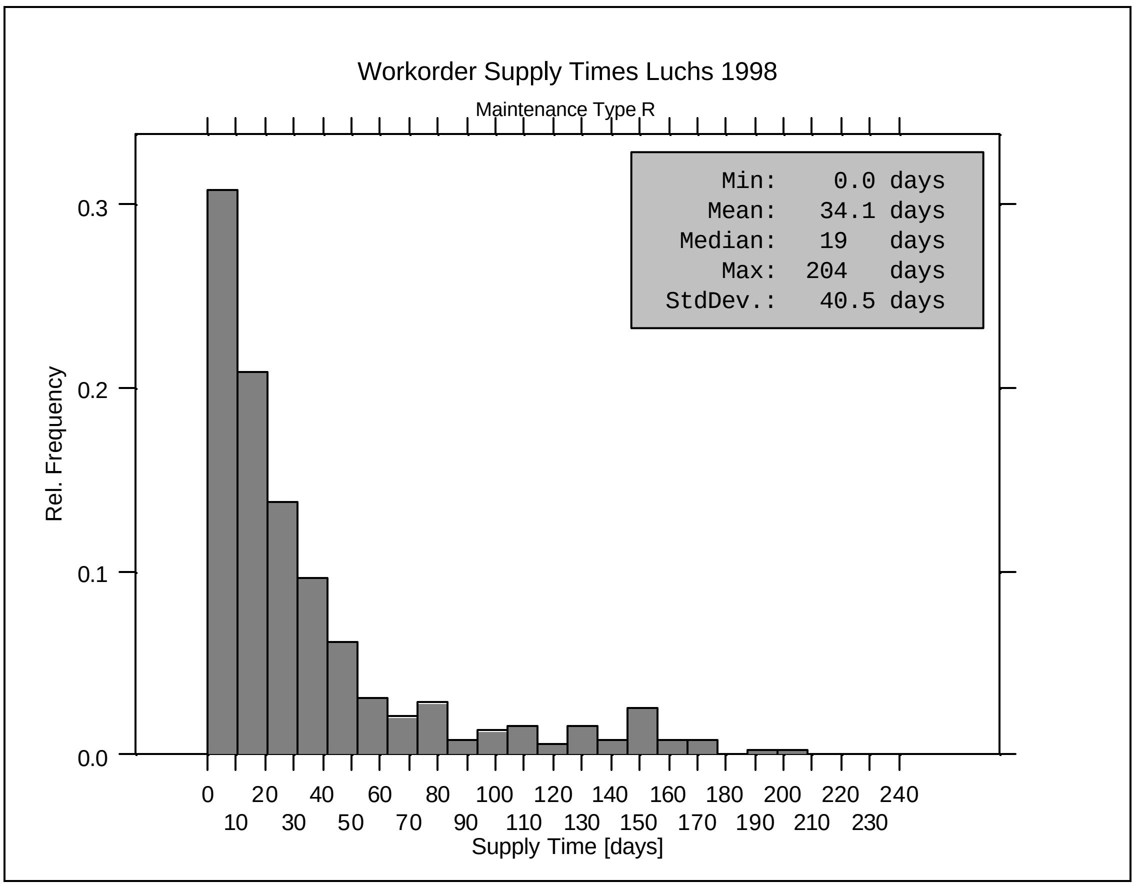

Figure 5.2 Workorder Supply Time Distribution (Vehicle).

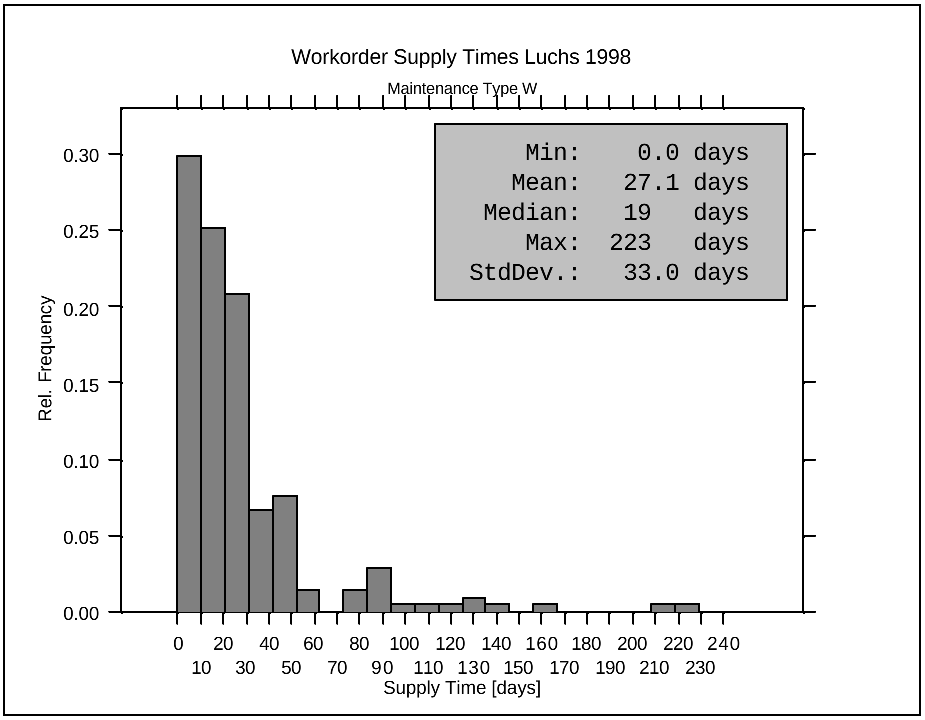

Figure 5.3 Workorder Supply Time Distribution (Weapon).

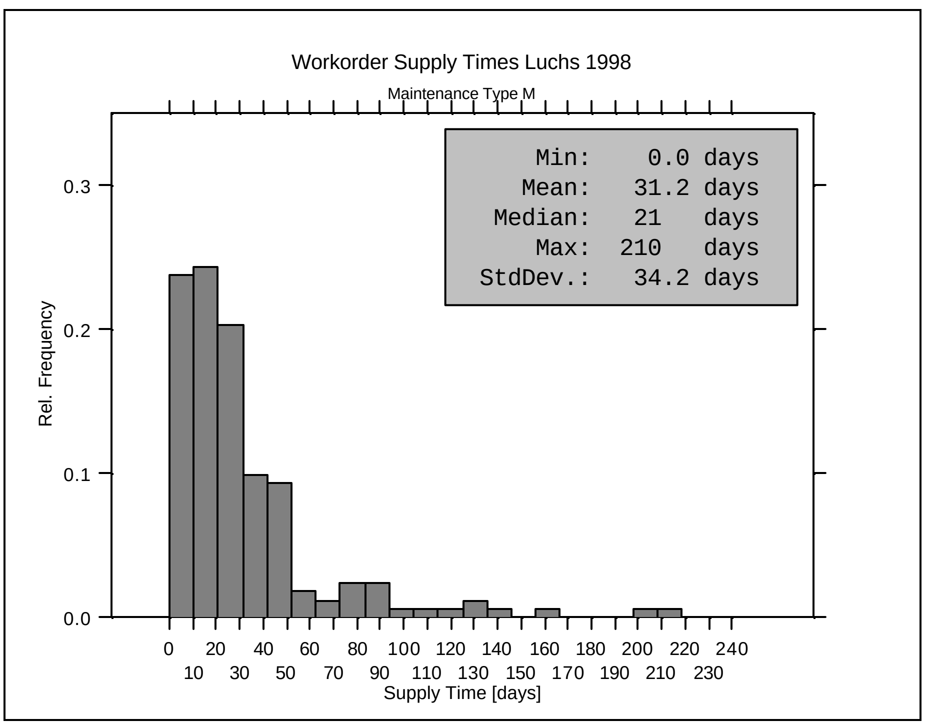

Figure 5.4 Workorder Supply Time Distribution (Radio).

The workorder supply time distributions for the different maintenance types have quite similar shapes and statistics. This is confirmed by Figure 5.5, which shows a plot of the density lines for the workorder supply times for the three maintenance types.

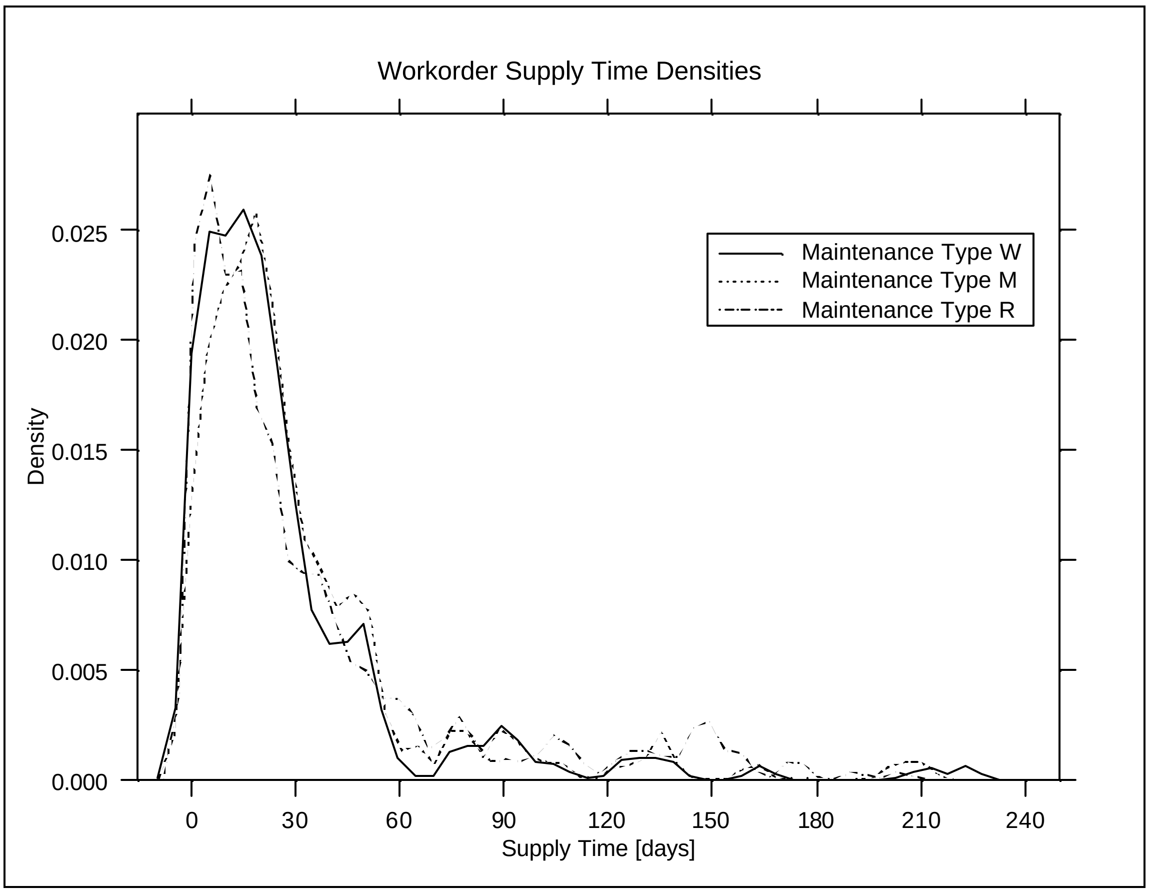

Figure 5.5 Comparison Between Density Lines.

The shapes of the supply time distributions suggest fitting a Weibull-model to the data. A generalized likelihood ratio test [Ref. 19] can be used to test the null hypothesis that all workorder supply times can be combined into one model against the alternative that a distinct model for each maintenance type is more appropriate. The p-value for the test in this case is 0.087, which means that the null hypothesis is not rejected at a test level of 5 percent. Therefore, a Weibull model is fitted to the combined supply times. The resulting parameter estimates together with their standard errors are:

$$\alpha = 0.886 \qquad SE(\alpha) = 0.0235$$

$$\beta = 29.692 \qquad SE(\beta) = 0.6764$$

Figure 5.6 compares the distribution of the 1998 supply times with the distribution of 100,000 random numbers generated from the Weibull-model:

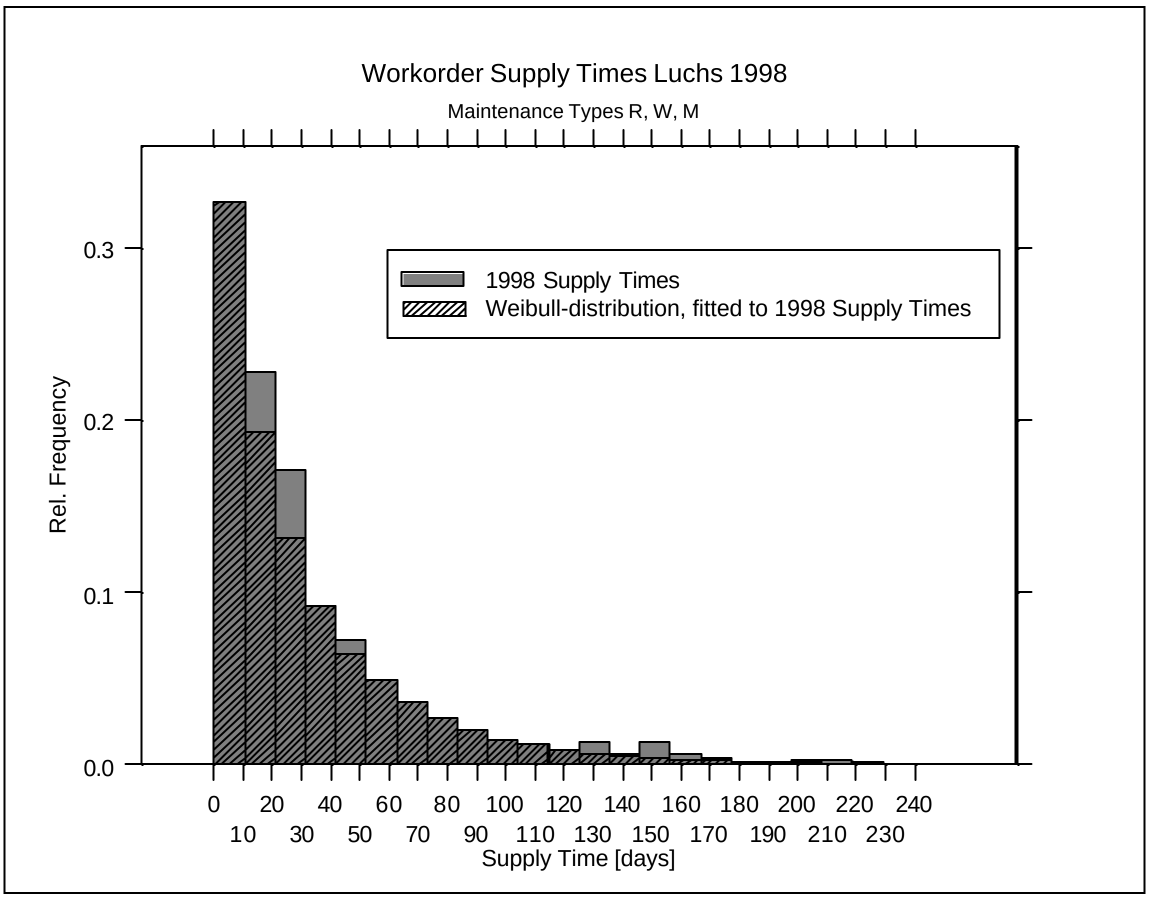

Figure 5.6 Workorder Supply Time Distribution vs. Weibull-model. *The model shows a good fit to the 1998 workorder supply times.*

Supply times depend on a variety of factors, which cannot be extracted from maintenance history data. Training and quality of personnel, scenario, budgetary factors, stockage policies, and degree of supervision are only a few of the important factors that have to be considered. This means that there is no general supply time distribution from which to generate in a simulation. Instead, different models are necessary for different scenarios. However, the workorder supply times shown in Figure 5.7 for the SFOR mission in Bosnia-Herzegovina do not differ significantly from those of regular peacetime supply. A permutation test [Ref. 21] using a two-sample Kolmogorov-Smirnov goodness-of-fit test yields a p-value of 0.453, which means that the null hypothesis (*regular and SFOR supply times come from the same distribution*) is supported.

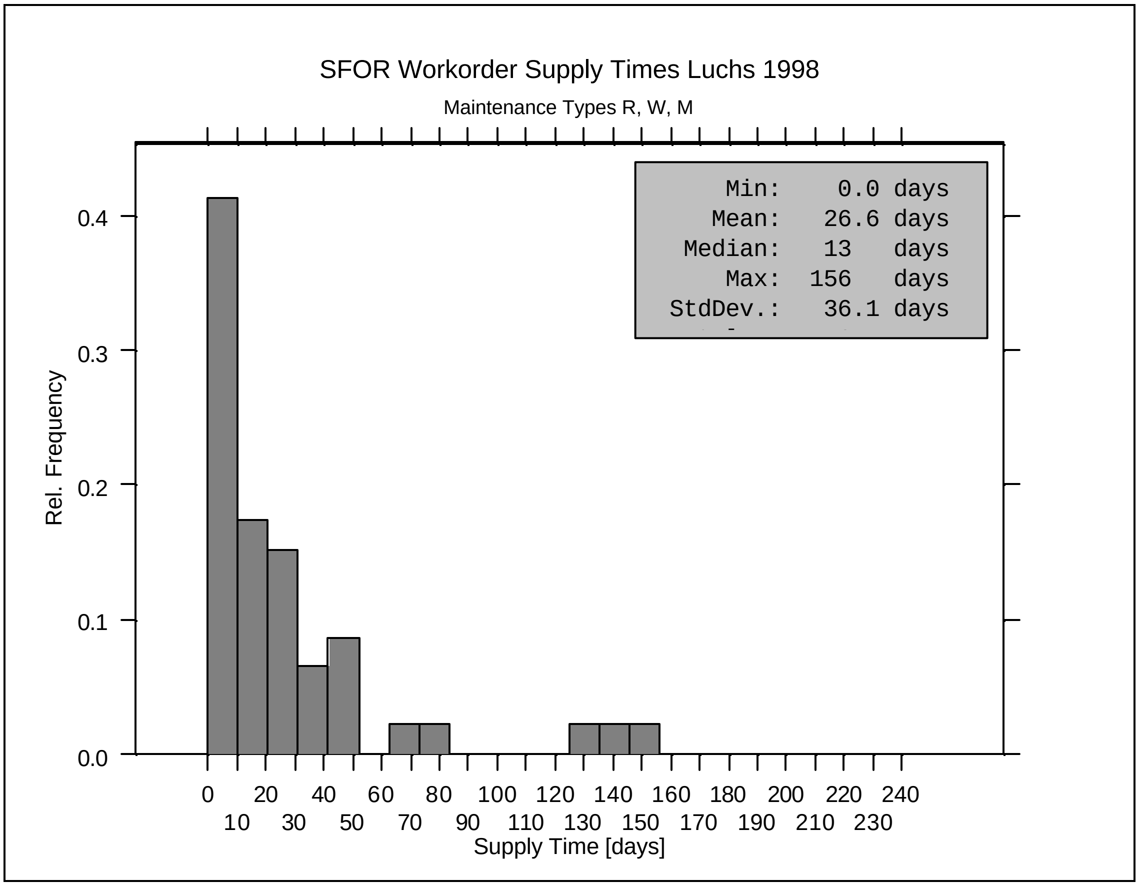

Figure 5.7 Workorder Supply Times SFOR.

D. WORKORDER SUPPLY TIME PROBABILITIES

Oftentimes, it is of particular interest to know the probability that a workorder is completely supplied with all spare parts within a specified time period. This probability can be estimated and visualized by graphing the empirical distribution function of a set of supply times [Ref. 18]. Figure 5.8 shows the empirical distribution function for the 1998 workorder supply times.

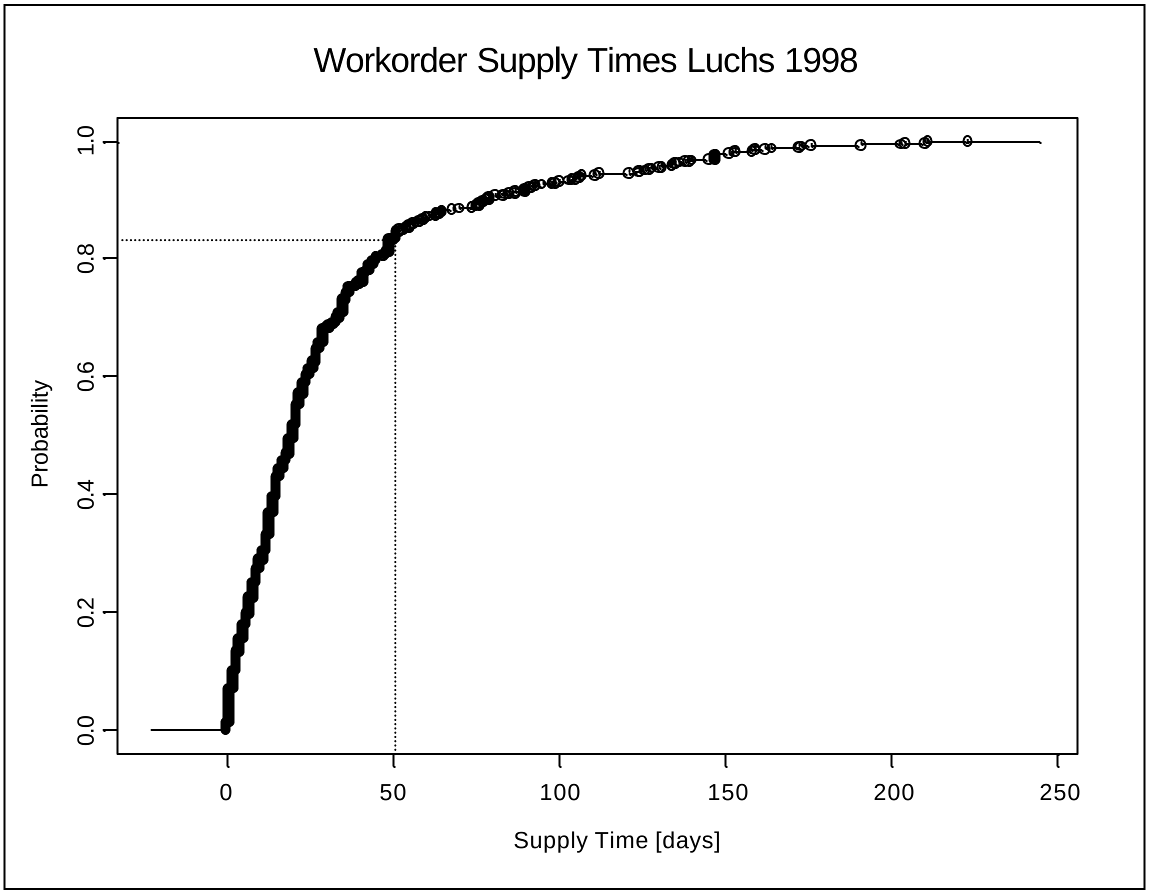

Figure 5.8 Empirical Distribution Function (EDF) of 1998 Workorder Supply Times. *The EDF is an estimator for the probability that a random variable is less than or equal to a certain value. Example: The probability that the workorder supply time is less than or equal 50 days is about 84% (dotted line). The empirical distribution function is a step-function with a discrete step at every supply time observation. This can be seen in the upper portion of the graph, where every dot corresponds to a single observation.*

Figure 5.9 compares the 1998 workorder supply times with the 1998 SFOR data.

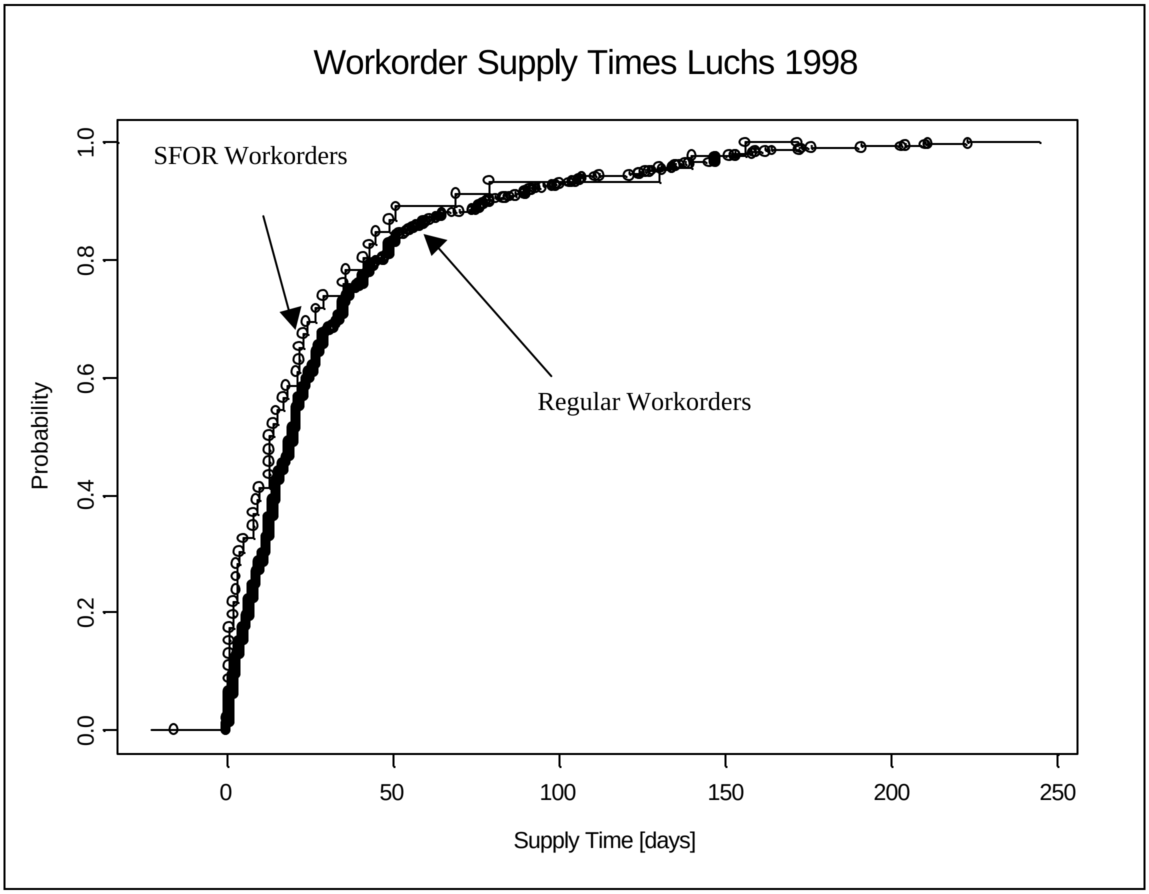

Figure 5.9 Comparison between Regular Workorder Supply Times and SFOR Workorder Supply Times. *This plot supports the results from the permutation test in Section C. The empirical distribution function of the 1998 SFOR workorder supply times has a similar shape as the distribution function of the regular workorder supply times.*

The graph of the empirical distribution function reveals the variability in the distribution of supply times and can give insights not achievable by only reporting averages. The supply time distributions shown in Section C are dramatically skewed by supply times that are more than two or three times the achieved average. Hence, a reduction in the variability seems at least as important as a reduction in average supply times. Figure 5.10 shows the empirical density functions of two differently shaped hypothetical distributions. Although they have identical means, they differ substantially in their variance.

Figure 5.10 Comparison between Samples from Distributions with Different Variances. *Both samples have a mean of 14 days. The sample from the uniform distribution has a standard deviation (SD) of 3.2 days, whereas the sample from the exponential distribution has a SD of 12.1 days. After 20 days all workorders from Sample 1 are supplied. At the same time, only about 70% of the workorders of Sample 2 are supplied.*

E. CONCLUSIONS

This chapter showed that both the supply times for single spare parts and the workorder supply times have exponential-shaped, skewed distributions with medians significantly smaller than the means. The standard deviations of these distributions are generally of the same magnitude as the means.

Section B developed the methodology of “critical spares,” which can help to identify and tackle supply problems by sorting spare parts according to their supply statistics. Furthermore, listings with spare parts used in the repairs of a certain type of equipment in the past can be used to crosscheck spare part assortments.

A suitable approach to model the spare part supply in a simulation is shown in Section C, where workorder supply times are extracted from the data. In the analyzed cases, these workorder supply times were independent from the maintenance type. Dependence from scenarios and the type of equipment is assumed. However, this assumption should be checked in further analyses. For the “Luchs,” the difference in the distributions of SFOR and regular workorder supply times was not statistically significant.

VI. VEHICLE MAINTENANCE HISTORY

A. INTRODUCTION AND OVERVIEW

Analyzing the maintenance history of single vehicles can give precious insights into how to model failures and scheduled maintenance activities of these vehicles. This chapter discusses the possibilities and problems associated with this kind of analysis.

SAM-Div, like many other publications, assumes an exponential distribution of the times between failures. The mean times between failures (MTBF) are specified in SAM-Div's *Data Module* for the different pieces of equipment, as well as for the different maintenance and mission types. Like many other parameters in the *Data Module*, these MTBF's together with their standard errors represent "educated guesses," which, in the process of "hardening" the database with real world data, must be replaced with numbers obtained by analyzing equipment lifecycles. Furthermore, the assumption of exponentially distributed times between failures has to be examined.

Analyzing available maintenance history data could be a way to verify this assumption and to obtain at least some of the MTBF's in cases where the assumption is met. However, since the available workorder records cover only peacetime operations, training exercises, and peace keeping missions, not all of the MTBF's used in SAM-Div can be obtained this way.

At least the following two preconditions on the data have to be satisfied to get accurate and usable results. First, enough vehicles of a certain type with a complete maintenance history are necessary to draw conclusions. A complete maintenance history over a given period means that all workorders, for both scheduled and corrective maintenance, have to be present in the database. Secondly, the data entries, which correspond to the dimension of the MTBF, have to be accurate. For instance, the MTBF for a truck is usually given in "miles driven," which means that the mileage entries in the workorders are crucial in making inferences about the truck's MTBF.

Section B addresses the completeness of maintenance histories, whereas Section C deals with the accuracy of MTBF-relevant data fields.

B. COMPLETENESS OF MAINTENANCE HISTORIES

The maintenance organization software generates workorder numbers in consecutive order for every maintenance facility. These workorder numbers are not related to the type of equipment. Therefore, there is no way to determine whether the available repair workorders for a certain vehicle is complete. For the part of scheduled maintenance, the situation is different. Scheduled maintenance activities are performed in regular time intervals and in a fixed order. This means that for every vehicle the same types of scheduled maintenance events in roughly the same amount should be present in the database. In the case of the Luchs in 1997, there are scheduled maintenance activities for 351 different vehicles present in the database. This represents 86 percent of the 409 Luchs-tanks existent in the German Army. The number of activities per single vehicle ranges from 1 to 25, with an average of 5. These facts demonstrate that the database is far from complete with regard to scheduled maintenance.

Chapter III demonstrated that the database consists of only 40 to 50 percent of the workorders. This means that the database is also not complete with regard to corrective maintenance. This leads to the conclusion that maintenance history records in their present format cannot be used to determine MTBF's.

C. ACCURACY OF MTBF-RELEVANT DATA

The database' completeness (or the lack thereof) is not the only problem regarding how to determine the MTBF's. The relevant data fields *mileage* and *rounds fired* show what Lionel A. Galway and Christopher H. Hanks call *operational data problems*. In their 1996 RAND study "Data Quality Problems in Army Logistics" [Ref. 7], Galway and Hanks state that *operational data problems* are present when data values are missing, invalid, or inaccurate. In 3.9 percent of the Luchs workorders in maintenance type R (vehicle), the entry for *mileage* is missing. Moreover, in 53.8 percent of the Luchs workorders in maintenance type W (weapon), the entry for *rounds fired* is missing. A manual inspection of nonmissing entries in the workorders for some vehicles reveals even more problems. Many vehicles have constant mileages throughout the year and then a huge increase at a certain point, whereas some vehicles toggle between two or three different mileage-levels. This also applies to the *rounds fired* entry. All this adds to the overall conclusion stated in Section D.

D. CONCLUSIONS

This chapter showed that tracking the lifecycles of specific vehicles or major assemblies is impossible due to data quality problems. This means that it is also impossible to extract failure-related parameters like the mean time between failures (MTBF) from the maintenance history database in its current format. The data quality problems, which lead to these conclusions, are the incompleteness of the workorder records and missing or invalid data entries.

VII. DATA QUALITY ISSUES

A. INTRODUCTION AND OVERVIEW

This chapter lists and discusses data quality issues, which evolved during the data analysis work of this thesis. In addition, the chapter presents some examples of data quality problems and gives recommendations on how to avoid them in a future maintenance organization software.

As shown in this and some of the previous chapters, the maintenance history database generated by the software currently in use has many problems. The introduction of new software gives the opportunity to reorganize the manner in which maintenance history data is collected. However, problems inherent in the current system must be addressed and avoided in the new system. The design of the database includes the data collection and the definition of the contents. Clearly, the development of this design is vital for the database's intended use. Therefore, the strongest efforts should be put into a consistent and compact design. It is very difficult, if not impossible, to fix design errors later. It is more than frustrating to have modern statistical software packages capable of performing all kinds of sophisticated data analysis on the data only to discover that the data quality is insufficient. The RAND report "Data Quality Problems in Army Logistics" [Ref. 7] showed that data quality problems are by far not the sole responsibility of the user who entered "bad data." Many problems arise from unclear definitions, awkward collection procedures, and disconnects between the facilities that generate and those that use the data.

Data problems can be categorized into: (1) those arising from the data structure and the handling of the data (generation, export, import), and (2) those caused by the user while entering the data into the system. Section B addresses the first category, whereas Section C addresses the second.

B. DATA STRUCTURE AND HANDLING

The major problem in the current system is the data loss occurring from the data-generating maintenance facility to the data-collecting agency. However, with the possibilities of data transfer technologies and protocols developed during the past years, solving this problem should not be hard.

The problem of data loss in the current system is worsened by the fact that each workorder is split into four records (Hx1 – Hx4), as described in Chapter III. If one of the four records of a workorder is lost, the whole workorder is potentially useless for analysis. Moreover, many analysis tasks require information from the different record types of a workorder at the same time. For instance, the extraction of supply times for a workorder requires data fields from both the Hx1 and Hx3-records. Therefore, relationships between the different types of files (Hx1 – Hx4) have to be created within the database. In connection with the huge file sizes, this can make processing the data extremely slow. Even worse, query results can be flawed whenever overlap information contained in two or more different records of the same workorder is processed. For instance, a query designed to extract the number of spare parts used for the Luchs in 1998, indicated that 2,750 periscopes were replaced during that year. This was a suspiciously high number, since there are only 409 Luchs-tanks in the German Army. A query design change revealed the correct number of 75 periscopes. The cause of the failure of the original design was the way Access handles related tables when *total calculations* are applied. The point here is that many difficulties and errors could be avoided if the data were not split into different files.

Another important issue is the question "What data should be collected in a maintenance history database?" Currently, each workorder generates a huge amount of data because every data field of the original workorder is included in its Hx1 – Hx4 records at least once. There is also overlap in the information between the different records, e.g., the workorder number is included eight times. The raw data description in Appendix B gives an impression of the amount of data generated by each workorder: 244 data fields with a total length of 1,837 characters. Many of those data fields are generally blank. Furthermore, whether many of the data fields can serve any purpose other than to use expensive hard disk space is highly questionable. For instance, it may or may not be useful to store the name of the truck driver who brought the truck into repair in the local archive of the maintenance facility. However, storing this name forever in the maintenance history database is certainly not useful. A careful design decision regarding what information should be included in the database is necessary. With the potential of a dramatic reduction in workorder record size, combining all the information of a workorder into only one record should not be a problem.

Currently, the data files are formatted as text files (.txt), probably the most universal format available. However, there are some disadvantages in handling this format. The major disadvantage is the danger of errors during the import of data into database software like Access. Because of the high amount of blank fields, Access does not recognize the correct format of the data. This means that the field specifications must be edited manually, a lengthy process prone to errors. A widespread format like Microsoft® Excel seems more suitable for data-handling purposes.

C. DATA QUALITY

This section lists some examples of data quality problems encountered during the data analysis part of this study. Most of these problems fall within the responsibility of the user who entered the data into the system. However, some of the problems are also related to vague definitions or bad input design.

The data field *Auftragsart* seems to have a low perceived value to the user. This data field is a code designed to distinguish between different kinds of workorders, e.g., *repair after accident*, *repair*, *scheduled maintenance level 2*, and so on. It is therefore potentially very useful for a selective analysis, e.g., of corrective maintenance workorders. In practice, however, this code cannot be used solely to filter the workorder types because 4.6 percent of the workorders coded as corrective maintenance belong to one of the other categories. In addition to this code, an additional query that checks the description of the workorder must be used to categorize the workorders correctly.

A more severe problem is the amount of blank or invalid data entries even in important data fields like *serial number*, *license plate number*, or *repairtime*. Nearly 20 percent (exactly 19.5 percent) of the Luchs workorders analyzed in this study did not contain the actual repairtime, while 8.5 percent did not contain the standard repairtime nor the actual repairtime. All in all, 12.3 percent of the workorders in this study had to be discarded due to missing or invalid data entries. A new software design should employ error-checking mechanisms to avoid such problems. Furthermore, the set of mandatory entries should be extended and the graphical user interface (GUI) should be designed according to principles based on the science of human factors.

Additionally, as many data entries as possible should be automated. For instance, the item names of equipment or spare parts should be linked to their stock number and filled in automatically. The Luchs workorders contained 41 (!) different names for the Luchs under one stock number. This can lead to false query-results whenever the analyst is not aware of this fact.

Strong efforts have to be made to improve the reliability of data entries. Examples include the data entries for *actual repairtime* and *mileage*, which were mentioned in earlier chapters. If these data entries are collected to analyze them later, solutions resulting in improved quality have to be found. If on the other hand, an analysis of these entries in the framework of the maintenance history database is not intended, then these data should not be collected.

Interestingly, the U.S. Army seems to have similar data quality problems. The 1996 RAND report "Data Quality Problems in Army Logistics" [Ref. 7] discusses many of the problems mentioned above. The authors, Lionel A. Galway and Christopher H. Hanks, conclude their report:

> *Force XXI characterizes information as an asset, perhaps the key asset of armed forces of the 21st century. While much of the attention has been focused on tactical and strategic information in support of effective combat operations, logistics information is just as much a key asset for support operations. But to be an asset, information must be built upon data of good quality. To have effective and efficient support, therefore, the Army will need to improve data quality in all parts of its logistics information systems. The kinds of problems we have discussed in this report will need to be attacked aggressively when discovered.*

Nothing has to be added to conclude this chapter.

VIII. SUMMARY AND RECOMMENDATIONS FOR FURTHER WORK

A. SUMMARY

Today's military is challenged with the need to plan, execute, and support missions in uncertain scenarios. Minimizing the risks and costs of such missions while still achieving the goals becomes more and more important. One important aspect in supporting any mission is to forecast the maintenance demand. Simulation, with proper output analysis, proves to be a suitable tool to deal with this kind of decision-making under uncertainty [Ref. 10]. However, the quality and accuracy of a simulation's output depends not only on the simulation model itself, but also on the quality of the data used in the simulation. Many current applications like the simulation part of SAM-Div suffer from the fact that their database consists of too many "educated guesses" instead of real world data.

This thesis shows that some of the major parameters in SAM-Div's *Data Module* can be extracted from existing maintenance history data. It uses the wheeled reconnaissance tank "Luchs" for demonstration purposes. The analysis focuses on repairtime distributions as an integral part of the repair process. A major conclusion is that repairtimes can be modeled as Weibull distributions with parameters depending on the type of equipment and the maintenance type. The Luchs repairtime-models analyzed in Chapter IV were built with 1997-1999 data and validated with data from 2000.

Modeling the workorder supply times is a reasonable way to simulate the supply with spare parts. Again, a Weibull distribution proves flexible enough to model this part of the maintenance process.

Chapter V develops a methodology to identify spare parts with critical supply characteristics. This is done by evaluating a "critical index" from the supply times, the number of orders, and a relevance factor for each spare part. The relevance factor specifies how important the spare part is for the functionality of its end item. This methodology can be used to tackle supply problems and to crosscheck other supply statistics, stocking policies, or spare part assortments for a mission.

Data quality issues analyzed in this thesis include the finding that only about 40 to 50 percent of all workorder records are present in the database. This proved to be a major obstacle in some parts of the analysis. For instance, it was not possible to investigate the maintenance history of single vehicles thorough enough to make statements about mean times between failures (MTBF). Among other data quality problems was a high amount of blank or invalid entries. About 10 percent of the records were excluded from the analysis due to invalid or blank entries. The data quality problems lead to the further conclusion that the maintenance history database in its current form is not suitable to track lifecycles of pieces of equipment or major assemblies.

B. RECOMMENDATIONS

In order to test the prototype of SAM-Div's simulation part, the database for a specific scenario like the current Kosovo peacekeeping mission should be filled with real world data from the mission. To get the parameters and data needed to run the simulation, maintenance records and recently collected data from Kosovo have to be analyzed according to the methodology developed in this thesis. After replicating the simulation sufficiently, the outcome analysis should produce a confidence interval for forecasted maintenance demand, which when can be compared to the actual demand. This approach could validate the SAM-Div simulation tool and lead to more accurate and reliable forecastings of maintenance demand. Furthermore, extracting parameters for systems other than the Luchs would show whether the findings presented in this thesis apply to other systems as well. The usability of the "critical spares" approach could also be checked within a case study "Kosovo."

The introduction of a new maintenance organization software is a great opportunity to dramatically improve the data quality. Avoiding any data loss and making appropriate database design changes as recommended in Chapter VII seems especially important. Finally, it is desirable to create a tool with a suitable GUI capable of analyzing and visualizing maintenance history data. This tool should be based on the new software and database design.

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APPENDICES

Appendix A contains a printout example of an actual maintenance workorder. It demonstrates the contents of the different record types Hx1 – Hx4. Furthermore, a sample from the raw data in text file format, and a sample from an Hx2-Access table, is included.

Appendix B contains the raw data descriptions for Hx1 – Hx4 files; these descriptions contain the field names, the types and the field lengths of the raw data files. This information is essential for importing the data into database management software and may be used for future anlalyses.

Appendix C describes the features of the German wheeled reconnaissance tank "Luchs."

Appendix D describes and lists the S-Plus code to estimate the parameters and standard errors of a Weibull model fitted to a given set of data.

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APPENDIX A: DATA SAMPLES

Example of a Maintenance Workorder (Description see page 82)

INST U. USTG KP DVU-VTT (MatErh)	Liste: 005	Datum: 16.08.2000 Seite: 001

I N S T A N D S E T Z U N G S A U F T R A G

R P 0 1 3 4 5

Datum	DStNr	Dienststelle	PLZ	Standort	Auftragskurzbezeichnung
9111	102858	TSH/FSHT STAB	52060	AACHEN	TMP MÄNGEL ABSTELLEN DF88

VersorgungsNr	Proj/Gerät/Bauteilbezeichnung	Endgerät: VersorgungsNr	Bezeichnung	Seriennummer
2320121587360	SPAEHPZ LUCHS 2	2320121587360	SpPz Luchs 8Rad	4243

Seriennummer	Amtl.Kennz	Bj/Erstinbetrb	EinsArt	BetrbLstg	Sonstige	Bemerkungen (Suchfeld)	Drgl	Vorrang
	Y 947601 / 4	76/0876	0	K 011456	T 000046	MW 079		5

Letzte TMatPrfg	Letzte DpInst	TANr	AnzahlGer	AuftrArt	Schaden n.SB	Name, Dstgrd
0499	0794 K 010636	0000	001	01		

<u>InstDstaTr:</u>

AuftrNr	AuftrDat	DstNr	DstBezeichnung	DurchfArt	AbrufPrfTrp	AbrufGer	AnnahmeGer	Name, Dstgrd
RP 1345	9112	46118	INST U. USTG KP	2		48	48	HECK-KARH.,OF
ArbBeg	**Arbunterbr**		**ArbEnde**	**AusgPrfg**	**Name,Dstgrd**	**ÜbergabeGer**		**Name, Dstgrd**
42	/							

<u>UInstEinh:</u>

AuftrNr	AuftrDat	DstNr	DstBezeichnung	DurchfArt	AbrufPrfTrp	AbrufGer	AnnahmeGer	Name, Dstgrd
ArbBeg	**Arbunterbr**		**ArbEnde**	**AusgPrfg**	**Name,Dstgrd**	**ÜbergabeGer**		**Name, Dstgrd**
	/							

<u>ZustInstEinh:</u>

AuftrNr	AuftrDat	DstNr	DstBezeichnung	DurchfArt	AbrufPrfTrp	AbrufGer	AnnahmeGer	Name, Dstgrd
ArbBeg	**Arbunterbr**		**ArbEnde**	**AusgPrfg**	**Name,Dstgrd**	**ÜbergabeGer**		**Name, Dstgrd**
	/							

PArt	PORG	Bewtg	fb	rf	nrf	Einstfg	Datum der Prüfung	PZeit(AW)	Name,Dstgrd,aaPNr
PArt	**PORG**	**Bewtg**	**fb**	**rf**	**nrf**	**Einstfg**	**Datum der Prüfung**	**PZeit(AW)**	**Name,Dstgrd,aaPNr**

ZNr	TDv	Bildtf	ÄI	OZ	SA	B	M	MES	RZ	Beschreibung der Störung	AZ	FR	ZNr	ArbPosNr	MES
001				000	10	2	2	1	1	BESTEHENDE INST-AUFTRÄGE:KA03656/KA00025/KA00718		RP	1	0	1
002				000	10	2	2	4		ZUBEHÖR:ABSCHLEPPGABEL VERFORMT,HALTER SACHE			1	0	
003				000	13	2	2	2		BREMSANLAGE:LÜFTSPIELDER RADBREMSE 3 ACHSE LINKS			25	0	
004				000	51	1	2			ZU GROß,BBA GRUNDEINSTELLEN SIEHE AUCH Z.NR:25			3	0	
005				000	21	1	1	2	15	EL.ANLAGE:KABELDURCHFÜHRUNGEN DES 1 BATTERIEKASTEN	15	RP	5	0	3
006				000						LOSE,BATTERIEPOLKLEMMEN ALLER BATTERIEN TEILWEISE			5	0	
007				000	21	1	1			ÜBERZOGEN,INST. UND ERNEUERN.			5	0	
008				000	20	1	0	2	10	KÜHLANLAGE:OBERE MUFFE DER SCHNELLKUPPLUNG	10	RP	8	0	2
009				000	20	1	0			HINTEN NICHT FEST,BEFESTIGEN.			8	0	
010				000	20	1	0	2	10	KÜHLANLAGE 2 BEFESTIGUNGSMUTTERN UND UNTERLEGSCH.	10	RP	10	0	3
011				000	20	1	0			FEHLEN UNTEN AM LÜFTER,NEU ANBRINGEN.			10	0	
012				000	10	2	2	3	60	BREMSANLAGE:VORRATSBEHÄLTER R F FLÜSSIGKEITSSTAND	63	RP	12	0	
013				000						NIEDRIG V F ZU HOCH,BEIDE ANSTEUERBLÖCKE(KREIS1U2)			12	0	
014				000						AUSTAUSCHEN(ANSTEUERKREIS IM BREMSBLOCK UNDICHT)			12	0	
015				000						(BREMSFLÜSSIGKEIT WIRD UMGEPUMT)			13	0	
016				000	10	2	2	3		BREMSANLAGE:HBZ,RF SETZT ZEITWEISE AUS,			12	0	
017				000	10	2	2			HAUPTBREMSZYLINDER ERN.,SIEHE KA-98/3656			12	0	
018				000	10	1	1	2	5	BREMSANLAGE:PRÜFANSCHLUSS DRUCKLUFT NACH PRÜFUNG	5	RP	18	0	3
019				000	10	1	1			UNDICHT,ERNEUERN.			18	0	
020				000	10	1	2	3	30	LENKUNG:SPERRZYLINDER DER VIERACHSLENKUNG AN DER		RP	20	0	

I N S T A N D S E T Z U N G S A U F T R A G

ZNr	TDv	Bildtf	ÄI	OZ	SA	B	M	MES	RZ	Beschreibung der Störung	AZ	FR	ZNr	ArbPosNr	MES
021				000						UMSCHALTUNG BEIDE UNDICHT,ERN			20	0	
022				000	33	2	2	2	30	LENKUNG:BEFESTIGUNGSMUTTER AN DER SCHUBSTANGE ZUR			22	0	
023				000						4 ACHSE ZUM WANNENDURCHTRIEB SCHEUERT AM UMLENKHEB			22	0	
024				000						SCHRAUBE UND MUTTER ERN.LENKGEOMETRIE PRÜFEN/EINST			22	0	
025				000	13	2	2	3	160	BREMSE:BREMSWIRKUNG BEI RÜCKWÄRTSFAHRT NICHT AUS-	163	RP	25	0	3
026				000		2	2			REICHEND,KOMPLETTE BREMSE REINIGEN U.EINSTELLEN.			25	0	
027				000	13	2	2	1		HINWEIS:FZG KONNTE NUR IM GRTRIEBENOTBETRIEB			25	0	
028				000						GEFAHREN WERDEN SIEHE KA 3656			27	0	
029				000	13	2	2	1		CO-PRÜFUNG HEIZUNG ÜBER ABC BELÜFTUNG I.O.28			25	0	
030				000	12	0	0	3	20	ABC:ANLAGE BAUT ZU GERINGEN ÜBERDRUCK AUF		RP	30	0	
031				000						WAFFENWIEGE IM BLENDENBEREICH UNDICHT,			30	0	
032				000						WAFFENBLENDENABDICHTUNG ERN. UND IM ANSCHLUSS			31	0	
033				000						ANLAGE ERNEUT AUF ÜBERDRUCK PRÜFEN			32	0	
034				000	10	2	2			TE 046 OF HECK-KARHAUSEN			1		
035				000	21	1	1			SES ELEKTROMATERIAL GMBH			5		
036				000	21	1	1			ALTE STRAßE 22, POSTFACH 1438, WEIL			5		
037				000	1	0		1	1	PUMPENBLOCK WIRD IN AUSBILDUNG EINGEBAUT		RP	37		

InstDstaTr:

SaRZeit	MatKosten	ArbKosten	FremdMatKosten	FremdArbKosten	Fremdlstg	AusgPZeit	SaArbZeit
342							266

UInstEinh:

SaRZeit	MatKosten	ArbKosten	FremdMatKosten	FremdArbKosten	Fremdlstg	AusgPZeit	SaArbZeit

ZustInstEinh:

SaRZeit	MatKosten	ArbKosten	FremdMatKosten	FremdArbKosten	Fremdlstg	AusgPZeit	SaArbZeit

MatGrp	MatNachwTrp	BerStgMat	MatGrp	MatNachwTrp	BerStgMat	ErsTGrp	BerStgMat	ErsTGrp	BerStgMat	ErsTGrp	BerStgMat
9286		9112	228		9112		9112		9112		

ZNr	BAK	VersorgungsNr	VersArtBezeichnung	AT	Mgef	HV	BelegNr	Mgel	Rgel	Stat	Mdez	BuchVermerk
001	A0C	1005121616231	PUMPENBLOCK		1		0228 1					
005	A0C	5940121992684	ADAPTER, BATTERIEAN				9286 10			CC		
005	A0C	5940121992685	ADAPTER, BATTERIEAN		6		9286 13	6	6	BB		
005	A0C	5325142259924	PASSE FIL				9286 15			BF		
005	A0C	5325142259924	PASSE FIL		2		9293 1			CZ		00002Anul
005	A0C	5325142259924	PASSE FIL				9306 11			BF		
005	A0C	5325142259924	PASSE FIL		2		0068 56			CP		00002Anul
005	DEZ	DA 200/280/15	PASSE FIL		2		0000			CZ		00002Anul
005	DEZ	DA200/280/15	KABELDURCHFÜHRUNG		6		0000	6	6			DB514/00
010	A0C	5310121635084	SCHEIBE INNEN ABG		2		9286 18	2	2	BF		
010	A0C	5310121433942	RING SICHERUNGS		2		9286 20	2	2	BF		
010	A0C	5310121564996	MUTTER, SECHSKANT-		2		9286 22	2	20	BF		
010	A0C	5310121635084	SCHEIBE, INNEN ABGE		2		9293 2			CZ		00002Anul
010	A0C	5310121564996	MUTTER, SECHSKANT-		2		9293 3			CZ		00002Anul
010	A0C	5310121635084	SCHEIBE, INNEN ABGE				9306 12			BP		
010	A0C	5310121564996	MUTTER, SECHSKANT-		2		9306 13	2	20	BF		
010	A0C	5310121433942	RING SICHERUNGS				0000					
010	A0C	5310121564996	MUTTER, SECHSKANT-				0000					
012	A0C	2590121597620	NEUANLAGE	X	2		9308 4002	2	2	BB		
018	A0C	4730121825444	VERSCHRAUBUNG PRÜF		1		9286 23	1	1	BF		

INST U. USTG KP　　　　　　Liste: 005　　　　　　Datum: 16.08.2000
DVU-VTT (MatErh)　　　　　　　　　　　　　　　　Seite: 003

I N S T A N D S E T Z U N G S A U F T R A G

ZNr	BAK	VersorgungsNr	VersArtBezeichnung	AT	Mgef	HV	BelegNr	Mgel	Rgel	Stat	Mdez	BuchVermerk
018	A0C	5330121564522	DICHTUNG		1		9286 24	1	1	BF		
018	A0C	4730121825444	VERSCHRAUBUNG, PR		2		9293 4			CZ		00002Anul
018	A0C	5330121564522	DICHTUNG		2		9293 5			CZ		00002Anul
018	A0C	4730121825444	VERSCHRAUBUNG, PR		2		9306 14	2	2	BF		
018	A0C	4730121825444	VERSCHRAUBUNG, PR				0000					
018	A0C	5330121564522	DICHTUNG				0025 12			BF		
018	A0C	5330121564522	DICHTUNG		2		0068 48	2	2			
020	A0C	2590121597619	NEUANLAGE		2		9286 25			BB		

ZNr	Btrblstg	SerienNr Schad	Btrblstg	SerienNr Gut	ZNr	Btrblstg	SerienNr Schad	Btrblstg	SerienNr Gut
000	000000		000000		000	000000		000000	

Benutzer: SCHRÖDER

Description:
The workorder shown above is a hardcopy printout of the data fields, which are processed within the maintenance organization software within each maintenance unit. These data fields are split up into four text files and sent as hidden files via floppy disk exchange to the next supply unit, from where they are transmitted electronically to data processing agencies.

The first part above the first table represents the Hx1-record of this workorder and is described in III.B.1. The first table within this workorder represents the Hx2-record described in III.B.2, whereas the second table represents the Hx3-record, which is described in III.B.3. The last table, here with only one “zero” row, contains the information for the Hx4-record desribed in III.B.4.

Sample of Raw Data (Hx4)

The sample shows eight Hx4-records within a Hx4 text file:

```
    36250 9 9700832 001 9700832 01 002 001 S 000001 85/02369           S
000001 92/42444           1997183070235612    980726
    71942 3 9700210 001 9700210 01 002 001 H 000100 89/28065           H
000001                                            0 020
    71942   9701108 001 9701108 01 002 001 H 000001 85/03016           H
000001 08737                                      0 020
    71942   9700578 002 9700578 02 001 001 H 000001 l9/504362          H
000001 2876858                                    0 020
    71942   9700578 001 9700578 01 001 001 H 000001 l9/535007          H
000001 2876775                                    0 020
    71942   9700519 001 9700519 01 056 028 H 000100 26656             H
000001 30824                                      0 020
    71892 4 9700942 001 9700942 01 001 001 H 001380 3025              H
001012 3632                                       0 012
    71892   9701074 001 9701074 01 010 013 K 033801 006074            K
000001 018560                                     0 031
```

Sample of Access-Imported Data

The sample shows an Hx2-table (Microsoft Access object):

Hx2_1997 : Table

ID	DStNr_Inst	AuftrNr	ZNr	Stoer	MES	RZ	Schaden	AZ	Fa
18	00004	9700001	001	024	1	15	REIFEN ABFAHRGRENZE ERREICHT,ERNEURN	15	RH
19	00004	9700002	001	012	3	1	SCHALTKUPPLUNG,KUPPLUNGSPEDAL H NGT INST		RH
20	00004	9700002	002	050	3	1	KUGELK\PFE VON LENKSTANGE AUSGESCHLAGEN,ERNI		RH
21	00004	9700002	003	001	3	1	ABGASUNTERSUCHUNG DURCHF!HREN		RH
22	00004	9700002	004	012			GEBER UND NEHMERZYLINDER, ERN		
23	00004	9700004	001	001	2	20	FRISTENARBEITEN F2 DURCHF!HREN	20	RG
24	00004	9700004	002	030	2	10	HALTER VON LUFTPRESSER GEBROCHEN,SCHWEI~EN	10	RG
25	00004	9700005	001	001	2	40	FRISTENARBEITEN F3 MIT OELWECHSEL DURCHF!HREN	40	RH
26	00004	9700005	002	013	2	25	WIRKUNG DER BBA UND FBA ZU GERING,BREMSEN REIN	25	RH
27	00004	9700005	003	013	2		UND EINSTELLEN		RH
28	00004	9700005	004	033	2	10	KRAFTSTOFFLEITUNG SCHEUERT AN LEITUNG ZUR VAKU	10	RH
29	00004	9700005	005	033	2		PUMPE,RICHTIG VERLEGEN		RH
30	00004	9700005	006	011	2	10	KRAFTSTOFFILTER VERSCHMUTZT,REINIGEN	10	RH
31	00004	9700005	007	022	2	5	BLINKERSCHALTER LOSE,BEFESTIGEN	5	RH
32	00004	9700005	008	023	2	5	LENKUNG SCHWERG NGIG,ACHSSCHENKEL ABSCHMIER	5	RH
33	00004	9700005	009	010	2	10	SCHLAUCH VONVAKUUMPUMPE UNDICHT,ABDICHTEN	10	RH
34	00004	9700013	001	001	2	1	OHNE ERKENNBARE M NGEL	1	RH
35	00004	9700013	002	001			BBA:54%, FBA:28%		
36	00004	9700018	001	001	3	1	ZWISCHENUNTERSUCHUNG DURCHF!HREN		RO
37	00004	9700006	001	031	3	10	SPRECHGARNITUR,ZUGENTLASTUNG GERISSEN,ERNEUE	0	MA
38	00004	9700006	002	000	1	1	NR.7421	0	MA
39	00004	9700006	003	019	3	5	ABDECKUNG FERNH\HRER FEHLT,ERNEUERN	0	MA

Record: 1 of 1490930

APPENDIX B: RAW DATA DESCRIPTIONS

Raw Data Description Hx1.txt

```
Name                             Null?    Type
-------------------------------- -------- ----
BAK                                       VARCHAR2(3)
DSTNR_INST                       NOT NULL VARCHAR2(5)
PZ_DSTNR                                  VARCHAR2(1)
AUFTRNR                          NOT NULL VARCHAR2(7)
ANZAHL_GER                                VARCHAR2(3)
JAHRZEHNT                                 NUMBER(5)
AUSSTDATUM                                NUMBER(10)
TE                                        VARCHAR2(3)
DSTNR_BTL                                 VARCHAR2(5)
PZ_DSTNRBTL                               VARCHAR2(1)
DSTNR_KP                                  VARCHAR2(2)
EINSART                                   VARCHAR2(1)
Y_NR_ART                                  VARCHAR2(8)
SERNR                                     VARCHAR2(18)
AUFTRKURZBEZ                              VARCHAR2(30)
VERSNR                                    VARCHAR2(15)
GERAETBEZ                                 VARCHAR2(20)
BJ                                        VARCHAR2(2)
ERSTBETR_MON_JAHR                         VARCHAR2(4)
BETRLEIST                                 VARCHAR2(7)
SONST                                     VARCHAR2(7)
LET_TMP                                   VARCHAR2(4)
LET_DEPINST                               VARCHAR2(4)
BEI                                       VARCHAR2(7)
TA_NR                                     VARCHAR2(10)
PL_NR                                     VARCHAR2(9)
ANZAHL                                    VARCHAR2(3)
AUFTRART                                  VARCHAR2(2)
SCHADNR                                   VARCHAR2(25)
SCHIRRKEY                                 VARCHAR2(8)
FR1                                       VARCHAR2(2)
AUFTRNR1                                  VARCHAR2(7)
AUFTRDAT1                                 NUMBER(10)
DSTNR1                                    VARCHAR2(6)
DSTBEZ1                                   VARCHAR2(20)
DFART1                                    VARCHAR2(1)
ABRFPRF1                                  NUMBER(10)
ABRGER1                                   NUMBER(10)
ANNGER1                                   NUMBER(10)
NAME11                                    VARCHAR2(15)
```

```
ARBBEG1                                   NUMBER(10)
ARBUNTERB1                                VARCHAR2(10)
ARBENDE1                                  NUMBER(10)
AGP1                                      NUMBER(10)
NAME12                                    VARCHAR2(15)
UEBERGGER1                                NUMBER(10)
NAME13                                    VARCHAR2(15)
FR2                                       VARCHAR2(2)
AUFTRNR_2                                 VARCHAR2(7)
AUFTRDAT2                                 NUMBER(10)
DSTNR2                                    VARCHAR2(6)
DSTBEZ2                                   VARCHAR2(20)
DFART2                                    VARCHAR2(1)
ABRFPRF2                                  NUMBER(10)
ABRFGER2                                  NUMBER(10)
ANNGER2                                   NUMBER(10)
NAME21                                    VARCHAR2(15)
ARBBEG2                                   NUMBER(10)
ARBUNTERB2                                VARCHAR2(10)
ARBENDE2                                  NUMBER(10)
AGP2                                      NUMBER(10)
NAME22                                    VARCHAR2(15)
UEBERGGER2                                NUMBER(10)
NAME23                                    VARCHAR2(15)
FR3                                       VARCHAR2(2)
AUFTRNR_3                                 VARCHAR2(7)
AUFTRDAT3                                 NUMBER(10)
DSTNR3                                    VARCHAR2(6)
DSTBEZ3                                   VARCHAR2(20)
DFART3                                    VARCHAR2(1)
ABRFPRF3                                  NUMBER(10)
ABRFGER3                                  NUMBER(10)
ANNGER3                                   NUM Name
BAK                                       VARCHAR2(3)
DSTNR_INST                       NOT NULL VARCHAR2(5)
PZ_DSTNR                                  VARCHAR2(1)
AUFTRNR                          NOT NULL VARCHAR2(7)
ANZAHL_GER                                VARCHAR2(3)
JAHRZEHNT                                 NUMBER(5)
AUSSTDATUM                                NUMBER(10)
TE                                        VARCHAR2(3)
DSTNR_BTL                                 VARCHAR2(5)
PZ_DSTNRBTL                               VARCHAR2(1)
DSTNR_KP                                  VARCHAR2(2)
EINSART                                   VARCHAR2(1)
Y_NR_ART                                  VARCHAR2(8)
SERNR                                     VARCHAR2(18)
AUFTRKURZBEZ                              VARCHAR2(30)
VERSNR                                    VARCHAR2(15)
GERAETBEZ                                 VARCHAR2(20)
BJ                                        VARCHAR2(2)
```

ERSTBETR_MON_JAHR	VARCHAR2(4)
BETRLEIST	VARCHAR2(7)
SONST	VARCHAR2(7)
LET_TMP	VARCHAR2(4)
LET_DEPINST	VARCHAR2(4)
BEI	VARCHAR2(7)
TA_NR	VARCHAR2(10)
PL_NR	VARCHAR2(9)
ANZAHL	VARCHAR2(3)
AUFTRART	VARCHAR2(2)
SCHADNR	VARCHAR2(25)
SCHIRRKEY	VARCHAR2(8)
FR1	VARCHAR2(2)
AUFTRNR1	VARCHAR2(7)
AUFTRDAT1	NUMBER(10)
DSTNR1	VARCHAR2(6)
DSTBEZ1	VARCHAR2(20)
DFART1	VARCHAR2(1)
ABRFPRF1	NUMBER(10)
ABRGER1	NUMBER(10)
ANNGER1	NUMBER(10)
NAME11	VARCHAR2(15)
ARBBEG1	NUMBER(10)
ARBUNTERB1	VARCHAR2(10)
ARBENDE1	NUMBER(10)
AGP1	NUMBER(10)
NAME12	VARCHAR2(15)
UEBERGGER1	NUMBER(10)
NAME13	VARCHAR2(15)
FR2	VARCHAR2(2)
AUFTRNR_2	VARCHAR2(7)
AUFTRDAT2	NUMBER(10)
DSTNR2	VARCHAR2(6)
DSTBEZ2	VARCHAR2(20)
DFART2	VARCHAR2(1)
ABRFPRF2	NUMBER(10)
ABRFGER2	NUMBER(10)
ANNGER2	NUMBER(10)
NAME21	VARCHAR2(15)
ARBBEG2	NUMBER(10)
ARBUNTERB2	VARCHAR2(10)
ARBENDE2	NUMBER(10)
AGP2	NUMBER(10)
NAME22	VARCHAR2(15)
UEBERGGER2	NUMBER(10)
NAME23	VARCHAR2(15)
FR3	VARCHAR2(2)
AUFTRNR_3	VARCHAR2(7)
AUFTRDAT3	NUMBER(10)
DSTNR3	VARCHAR2(6)
DSTBEZ3	VARCHAR2(20)

DFART3	VARCHAR2(1)
ABRFPRF3	NUMBER(10)
ABRFGER3	NUMBER(10)
ANNGER3	NUM NUMBER(9)

Raw Data Description Hx2.txt

```
Name                            Null?     Type
------------------------------- -------- ----
BAK                                       VARCHAR2(3)
DSTNR_INST                      NOT NULL  VARCHAR2(5)
PZ_DSTNR                                  VARCHAR2(1)
AUFTRNR                         NOT NULL  VARCHAR2(7)
ZNR_SERAV_DUP                             VARCHAR2(3)
AUFTRNR_SERAV_DUP                         VARCHAR2(7)
ZNR_1                           NOT NULL  VARCHAR2(3)
TDV                                       VARCHAR2(1)
BTNR                                      VARCHAR2(5)
AENDIDX                                   VARCHAR2(1)
OZ                                        VARCHAR2(3)
STOERART                                  VARCHAR2(3)
E                                         VARCHAR2(1)
M                                         VARCHAR2(1)
MES                                       VARCHAR2(1)
RZ                                        NUMBER(5)
SCHADEN                                   VARCHAR2(50)
ARBZ                                      NUMBER(5)
FR                                        VARCHAR2(2)
MESDURCHG                                 VARCHAR2(1)
ZNR_2                                     VARCHAR2(3)
APNR_1                                    VARCHAR2(2)
APNR_2                                    VARCHAR2(5)
APNR_3                                    VARCHAR2(1)
EINSATZ                                   VARCHAR2(1)
BELNR                                     VARCHAR2(16)
ID                                        NUMBER(9)
TE                                        VARCHAR2(3)
```

Raw Data Description Hx3.txt

```
Name                            Null?    Type
------------------------------- -------- ----
BAK                                      VARCHAR2(3)
DSTNR_INST                               VARCHAR2(5)
PZ_DSTNR                                 VARCHAR2(1)
AUFTRNR                                  VARCHAR2(7)
ZNR_SERAV_DUP                            VARCHAR2(3)
AUFTRNR_SERAV_DUP                        VARCHAR2(7)
SCHADZNR                                 VARCHAR2(3)
ZNR                                      VARCHAR2(3)
VERSNR                                   VARCHAR2(15)
ARTBEZ                                   VARCHAR2(20)
AUSTT                                    VARCHAR2(1)
HV                                       VARCHAR2(1)
BTK                                      VARCHAR2(1)
BELEGDST                                 VARCHAR2(5)
BELEGDATUM                               VARCHAR2(4)
BELEGNUMMER                              VARCHAR2(4)
STATK                                    VARCHAR2(2)
MGGEF                                    NUMBER(6)
MGGEL                                    NUMBER(6)
RESTGEL                                  NUMBER(6)
MGDEZ                                    NUMBER(6)
MGAC1                                    NUMBER(6)
MGGEF_UE                                 NUMBER(6)
JAHRZEHNT_EINGANG                        VARCHAR2(1)
EINGANG                                  VARCHAR2(4)
JAHRZEHNT_BRSTLG                         VARCHAR2(1)
MATBERSTG                                VARCHAR2(4)
BUCHVERM                                 VARCHAR2(20)
BAK_SCHIRR                               VARCHAR2(3)
BZEK                                     VARCHAR2(2)
EIGK                                     VARCHAR2(2)
ZUSAN                                    VARCHAR2(6)
PROJK                                    VARCHAR2(3)
AVS                                      VARCHAR2(2)
HWK                                      VARCHAR2(2)
BK                                       VARCHAR2(1)
ZK                                       VARCHAR2(1)
AK                                       VARCHAR2(1)
BEMERK                                   VARCHAR2(20)
AUFTRABSCHL                              VARCHAR2(1)
KLAM                                     NUMBER(5)
DEZFLAG                                  VARCHAR2(1)
TDVANG                                   VARCHAR2(15)
SEITE                                    VARCHAR2(4)
OZ                                       VARCHAR2(3)
GAPL                                     VARCHAR2(6)
```

BTNR	VARCHAR2(5)
DOUBLE_KEY	VARCHAR2(13)
MGR_L	NUMBER(10)
BELNR	VARCHAR2(16)
ID	NUMBER(9)
TE	VARCHAR2(3)

Raw Data Description Hx4.txt

```
Name                           Null?    Type
------------------------------ -------- ----
BAK                                     VARCHAR2(3)
DSTNR_INST                              VARCHAR2(5)
PZ_DSTNR                                VARCHAR2(1)
AUFTRNR                                 VARCHAR2(7)
ZNR_SERAV_DUP                           VARCHAR2(3)
AUFTRNR_SERAV_DUP                       VARCHAR2(7)
BGRP_ZNR                                VARCHAR2(2)
SCHDZNR                                 VARCHAR2(3)
ETZNR                                   VARCHAR2(3)
SBG_ART                                 VARCHAR2(1)
SBG_LSTG                                VARCHAR2(6)
SBG_SERNR                               VARCHAR2(18)
GBG_ART                                 VARCHAR2(1)
GBG_LSTG                                VARCHAR2(6)
GBG_SERNR                               VARCHAR2(18)
BELNR                                   VARCHAR2(16)
ID                                      NUMBER(9)
TE                                      VARCHAR2(3)
```

APPENDIX C: DESCRIPTION OF THE "LUCHS" TANK

Armored Reconnaissance Vehicle "Luchs"

- Engine Power: 287 kW (390 hp)
- Speed: 90 km/h
- fully amphibious
- Range: about 730 km
- Crew: 4
- Inventory: 409
- Armament:
  - 20 mm Machine Gun
  - Rate of Fire: 800-1000 rounds/min
  - Effective Range: up to 2000 m

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APPENDIX D: MAXIMUM LIKELIHOOD ESTIMATION

This topic is briefly discussed in [Ref. 16]. The following descriptions, explanations, and S-Plus code fragments were taken from [Ref. 17]. The text and code were adapted for the maximum likelihood estimation (MLE) of the parameters of a Weibull distribution to fit this model to a given set of data.

1. Maximum likelihood estimation of the parameters:

The *likelihood function* $L(a,b)$ is the product of the densities evaluated at the data values, treated as a function of the parameters. The MLE is obtained by maximizing this function. Equivalently, the MLE is obtained by maximizing the *log-likelihood function*, which is the natural logarithm of the likelihood function. In the present case the log-likelihood function is expressed as follows:

$$\ell(a, \beta) = n\log(a) - na\log(\beta) + (a-1)\sum_{j=1}^{n}\log(X_j) - \sum_{j=1}^{n}(X_j/\beta)^a$$

Maximizing this function would entail finding the first derivatives with respect to a and b and setting them equal to zero. This cannot be done in closed form. Therefore, a computer must be used. The steps to find the MLE in S-Plus are the following:

<u>**Step 1.**</u> Write a function (called **`LLFWEIB`** here) to calculate minus the log-likelihood, as shown below:

```
function(theta)
{
# LLFWEIB
#
# Returns the negative of the Weibull log-likelihood function.
# Minimizing LLFWEIB is the same as maximizing the
# likelihood
#
# Data for the problem must be contained in vector x,
# existing in the workspace.
#
     a <- theta[1]
     b <- theta[2]
     llk <- sum(log(dweibull(x, a, b)))
     return( - llk)
}
```

Step 2. Create the data vector and select a starting value for the solution.

```
> x <- LuchsR[,4]     # column of repairtimes
> startval <- c(.1,5) # may need to use trial and error
```

Step 3. Invoke **`NLMINB`** **(**built-in S-Plus function to minimize a function). The solution is the first list element.

```
> ylist <- nlminb(startval,llfweib,lower = c(.01,.01))
> ylist[[1]]
[1] 0.8620241  191.3037296
```

The MLE is $\hat{\alpha} = 0.862$ and $\hat{\beta} = 191.30$. Note that trial and error may be needed to find the solution. When you do find a solution, it is a good idea to rerun **NLMINB** several times with different starting values to make sure that you get the same answer each time.

2. Standard errors of maximum likelihood estimators:

Under certain mathematical conditions, which are generally met for Weibull models, MLEs have standard errors that are easy to approximate. It involves taking all second partial derivatives of the log-likelihood function, which will be referred to as $\ell(?)$. Here, q may be a vector. In the above Weibull example, q was the 2-vector (a, b). There are four second partial derivatives, which we can arrange into a 2×2 matrix called the <u>Hessian</u>, which will be denoted H. In the Weibull example, the second derivatives are given below:

$$H(1,1) = \frac{\partial^2 \ell}{\partial a^2} \quad = \quad -\frac{n}{a^2} - \sum_{j=1}^{n} (X_j / ß)^a [\log(X_j / ß)]^2$$

$$H(1,2) = H(2,1) = \frac{\partial^2 \ell}{\partial a \partial ß} \quad = \quad -\frac{n}{ß} + \frac{1}{ß} \sum_{j=1}^{n} (X_j / ß)^a \, [1 + a \log(X_j / ß)]$$

$$H(2,2) = \frac{\partial^2 \ell}{\partial ß^2} \quad = \quad \frac{na}{ß^2} - \frac{a(a+1)}{ß^2} \sum_{j=1}^{n} (X_j / ß)^a$$

The procedure for finding the estimated covariance matrix of the MLEs is as follows:

Step 1. Substitute the MLEs into the second partial derivatives: *H*(1,1), *H*(1,2), *H*(2,1), and *H*(2,2) in the above example. Use S-Plus to calculate these terms.

Step 2. The estimated covariance matrix is **minus the inverse of the Hessian**.

Step 3. The standard errors are the square roots of the diagonal elements of the covariance matrix.

The following S-Plus code performs the necessary calculations:

```
> a <- ylist[[1]][1]
> b <- ylist[[1]][2]
> n <- 3913 #sample size
> H <- matrix(0,2,2)
> xb <- x / b
> H[1,1] <- -n/(a^2) - sum((xb^a)*log(xb)^2)
> H[1,2] <- -n/b + sum((xb^a)*(1 - a*log(xb)))/b
> H[2,1] <- H[1,2]
> H[2,2] <- n*a/(b^2) - a*(a+1)*sum(xb^a)/(b^2)
> V <- -solve(H)  # This is the matrix inverse function
> sqrt(diag(V))
[1] 0.0098283 1.9795037
```

The estimated standard errors are $SE(\hat{\alpha}) = 0.0098$ and $SE(\hat{\beta}) = 1.9795$.

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