TROUBLESHOOTING AND HUMAN FACTORS IN AUTOMATED MANUFACTURING SYSTEMS

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by

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Foreword

This book is an empirical study of troubleshooting and human factors in automated manufacturing systems. Troubleshooting—the process of locating and diagnosing a fault in a system—is often difficult for the maintenance specialist in a computer-controlled manufacturing system. Underlying this difficulty is the fact that manufacturing systems are getting more complex. Difficulties encountered by expert troubleshooters as they acquire and use information to diagnose faults are identified. Suggestions are provided for ways to design computer-controlled manufacturing systems, and in particular process control technology, to alleviate these difficulties.

The book investigates how manufacturing systems can be designed and, in particular, the process control technology needed to make troubleshooting easier for the maintenance specialist. The approach employed is to understand how maintenance specialists acquire and use information during troubleshooting and the type of difficulties they encounter in doing this. The following questions are addressed:

- What information do troubleshooters use?
- How do they get the information they use?
- How do they use the information they have?
- How does presentation of information affect troubleshooting?
- What makes troubleshooting difficult?

The study is presented in three parts:

- Semi-structured interviews with expert troubleshooters
- Observation of plant-floor troubleshooting episodes

- A computer-based experiment investigating the effects of hierarchial representations of process control logic on fault diagnosis performance

The information in the book is from *Investigating Causes of Maintenance Downtime and Troubleshooting Difficulty in Computer-Integrated Production Systems,* by Susan R. Bereiter and Steven M. Miller of Carnegie Mellon University for the National Science Foundation, May 1988. Susan Bereiter completed this work for her doctoral dissertation. Professor Steven Miller was her thesis supervisor. Professors Granger Morgan, James Rinderle, and Alfred Spector, all of Carnegie Mellon, are acknowledged for their substantial contributions as members of Susan Bereiter's thesis committee.

The table of contents is organized in such a way as to serve as a subject index and provides easy access to the information contained in the book.

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Final determination of the suitability of any information for use contemplated by any user, and the manner of that use, is the sole responsibility of the user. The book is intended for informational purposes only. Its purpose is to aid in the design of improved systems to help maintenance and troubleshooting personnel in locating problems, *not* to present specific maintenance solutions to these problems. Expert advice should always be obtained when implementation is being considered.

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Contents and Subject Index

1. Introduction

The Problem:

Troubleshooting - the process of locating and diagnosing a fault in a system - is often difficult for the maintenance specialist in a computer-controlled manufacturing system. Underlying this difficulty is the fact that manufacturing systems are getting more complex. For example, process control computers on the shop floor are performing more sophisticated tasks, and these controllers are being linked together into more highly integrated systems. A troubleshooter working with a modern manufacturing system typically faces a large system of many parts, where each part is complex in itself, and where parts are interconnected in complex ways. It is no wonder that the troubleshooter often encounters difficulties with understanding system functions, isolating symptoms, and using information to structure a diagnostic search.

The Research Question:

How can we design manufacturing systems, and in particular the process control technology, to make troubleshooting easier for the maintenance specialist? Our approach to answering this question is to understand how maintenance specialists acquire and use information during troubleshooting and the types of difficulties they encounter in doing this. We address the following questions:

- What information do troubleshooters use?
- How do they get the information they use?
- How do they use the information they have?
- How does presentation of information affect troubleshooting?
- What makes troubleshooting difficult?

Understanding how troubleshooters use information can guide us in improving the design of computer-based troubleshooting support systems so that they aid a person in this task. An understanding of the characteristics of troubleshooting episodes that make troubleshooting difficult can help us focus effort to eliminate these characteristics or to help people overcome them. This information can also be useful to people who work on other aspects of troubleshooting, such as managers and trainers. For example, documentation of how expert troubleshooters use information to isolate faults can lead to insight into how to train other troubleshooters to become experts.

An alternative research approach would have been to directly proceed to the design of user interfaces and support systems for troubleshooters. However, we could not justify proceeding directly to generating designs without first understanding more about the process of troubleshooting. Rouse [38] calls such a strategy one of "user-centered design," in that the design objectives are oriented toward providing means to help users achieve the operational objectives for which they are responsible. Norman [32] has also cited the importance of developing theoretical tools to understand what a user is doing. This is in contrast to "technology-driven design," in which the technology is considered before the user. There have been too many problems resulting from technology-driven design practices. In our context, we have seen automation systems designed to optimize performance characteristics such as cycle time at the expense of ease of troubleshooting. Even more surprising are examples where designers set out to help troubleshooters and fail to do so. For example, during the course of out plant visits, we have seen fancy (and expensive) "enhanced" displays that have sat in the corner, unused. An even worse situation occurs when the "diagnostic aids" turn out to be detrimental. Rouse [38] describes a high-tech injection molder control system, where the introduction of color-graphic displays and keyboards resulted in a relatively easy job becoming quite difficult. We have seen cases where the sophisticated color-graphic displays to controllers were mismatched to the troubleshooters' needs, and people were spending their spare time drawing special diagrams to help them find the information they needed from the controller.

The Motivation:

Some manufacturers who invested in sophisticated computer-controlled manufacturing equipment are finding that the technologies do not perform as well as initial expectations. While these new automated systems offer the potential for a company to regain a competitive edge by increasing product quality, decreasing production costs, and increasing flexibility, users of such systems are finding that it is difficult to keep

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the new production processes operating. Downtime is a major problem and is expensive in terms of repair costs and lost revenue. The automobile industry, a leader in the application of computer-controlled manufacturing systems, has indicated that it plans to slow down the rate of investment in computer-controlled manufacturing systems, partly because downtime is more excessive and systems are more costly than expected [3][23] [30] [29] [55].

Results of a Case Study:

To investigate first-hand the extent to which downtime is a problem in computer-controlled manufacturing systems, we analyzed downtime data from the body shop of one vehicle assembly plant which was recently modernized from 1950's-vintage "hard-automated" and manual production processes to highly computerized processes. A thorough description of the data analysis is included in [1].

Downtime:

The downtime data cover a one-year period, starting six months after the start of production. Figure 1-1 shows an estimate of the percent of total production time that was lost because of failures during the year studied. The graph indicates that downtime is indeed a problem at the plant studied. The graph clearly shows that the fraction of production time that the plant was not operating ("down") fell over the year from about 15 percent to about five percent. Such a reduction can be expected, since the number of failures in the plant should fall as the "bugs" are worked out and as maintenance personnel become more adept at tracing and fixing failures. In a high-volume, high value-added facility such as the one studied here, even five percent downtime can mean significant cost in terms of lost revenue. Five percent downtime over a 2-shift, 8-hour per shift day is 48 minutes of downtime. Assuming a typical production line rate of 60 vehicles per hour, 48 minutes of downtime means 48 vehicles are not produced. At about $10,000 to $15,000 per vehicle, this amounts to roughly half to three quarters of a million dollars in lost revenue each day.

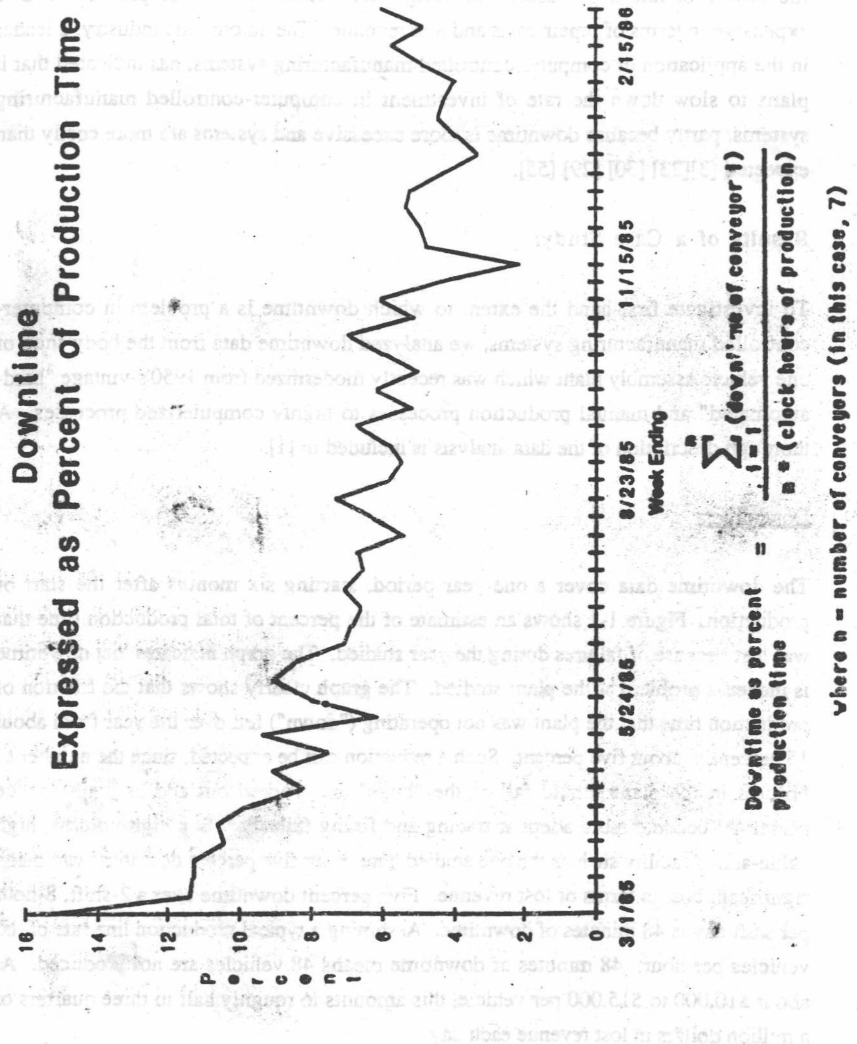

Downtime
Expressed as Percent of Production Time
Percent
16
14
12
10
8
6
4
2
0
3/1/85
5/24/85
8/23/85
11/15/85
2/15/86
Week Ending
Downtime as percent production time = $\sum_{i=1}^{n}$ (downtime of conveyor i) / n * (clock hours of production)
where n = number of conveyors (in this case, 7)

Figure 1-1

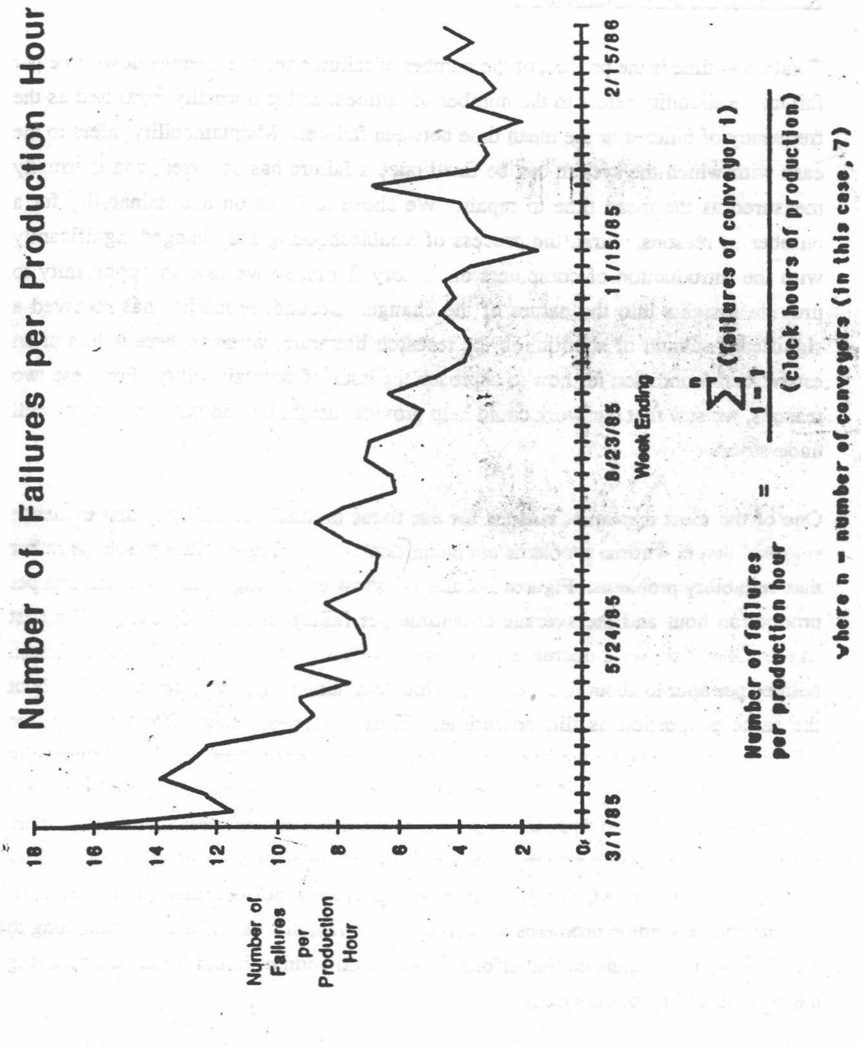
Reliability versus Maintainability:

Total downtime is the product of the number of failures and the average downtime per failure. Reliability refers to the number of failures, and is normally measured as the frequency of failures or the mean time between failures. Maintainability refers to the ease with which the system can be fixed once a failure has occurred, and is usually measured as the mean time to repair. We chose to focus on maintainability for a number of reasons. First, the process of troubleshooting has changed significantly with the introduction of computers o. .ory floors, so we saw an opportunity to provide insights into the nature of the change. Second, reliability has received a significant amount of attention in the research literature, whereas there is less of an established foundation for how to approach the issue of maintainability. For these two reasons, we saw that our work could help provide insight into an issue that is not well understood.

One of the most important reasons for our focus on maintainability is that evidence suggests that downtime problems are being driven by maintainability problems rather than reliability problems. Figures 1-2 and 1-3 show the average number of failures per production hour and the average downtime per failure in the body shop. The first figure clearly shows a decrease in failure frequency over time, from about sixteen failures per hour to about four per hour. Note that failure frequency decreased by about the same proportion as did downtime. Thus, it appears that efforts to improve reliability at the plant have been succeeding. The second figure shows the surprising result that downtime per failure actually increased over time. One would expect downtime per failure to decrease over time as the maintenance personnel become more familiar with the new production system. The number of failures fell considerably during the year studied, yet downtime per failure did not decrease at all. Thus, it appears that downtime problems are driven by the fact that the failures take too long to fix. This seems to indicate that efforts to reduce downtime should focus on improving the maintainability of the system.

The Research Approach:

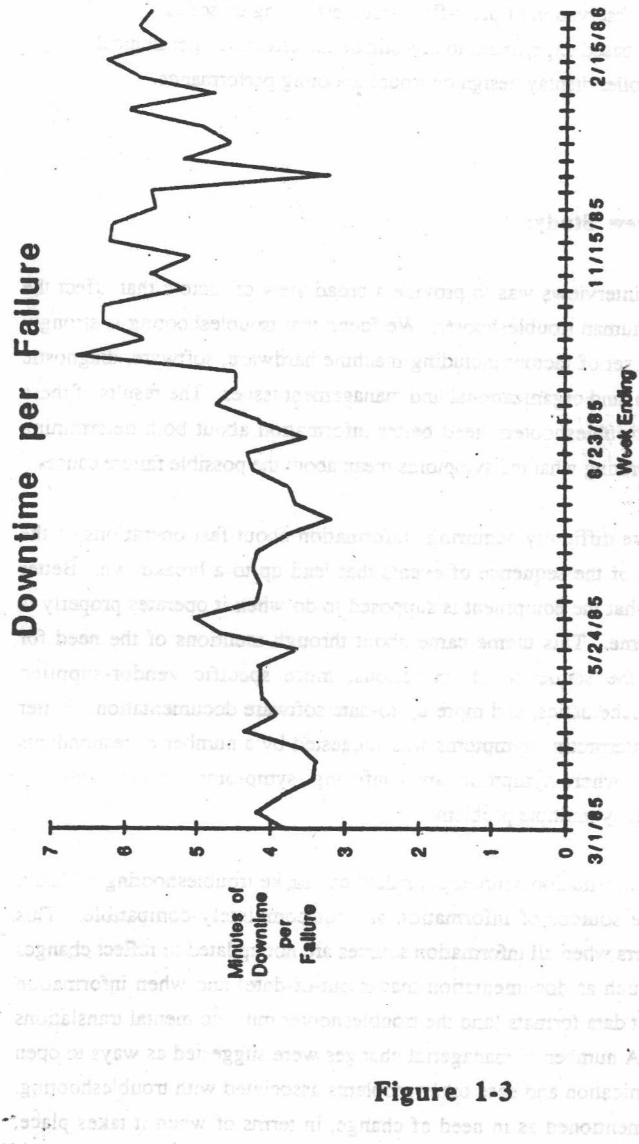
We have chosen to take a three-pronged approach for this study:



$$\text{Number of failures per production hour} = \frac{\sum_{i=1}^{n} (\text{failures of conveyor } i)}{(\text{clock hours of production})}$$

where n = number of conveyors (in this case, 7)

Figure 1-2



$$\text{Downtime per failure} = \frac{\sum_{i=1}^{n} \text{(downtime for conveyor i)}}{\sum_{i=1}^{n} \text{(failures of conveyor i)}}$$

where n = number of conveyors (in this case, 7)

Figure 1-3

* semi-structured interviews with expert troubleshooters
* field-based observation of plant-floor troubleshooting episodes
* a computer-based experiment to investigate the effects of hierarchical process controller display design on troubleshooting performance.

The Results:

Results of Interview Study:

One purpose of the interviews was to provide a broad view of factors that affect the performance of the human troubleshooter. We found that troubleshooting is strongly affected by a varied set of factors including machine hardware, software, diagnostic tools, documentation, and organizational and management issues. The results of these interviews suggest troubleshooters need better information about both determining symptoms and interpreting what the symptoms mean about the possible failure causes.

Troubleshooters have difficulty acquiring information about fast operations of the process and records of the sequence of events that lead up to a breakdown. Better information about what the equipment is supposed to do when it operates properly is also a recurring theme. This theme came about through mentions of the need for documentation of the sequence of operations, more specific vendor-supplied documentation and schematics, and more up-to-date software documentation. Better information about interpreting symptoms was suggested by a number of respondents who cited situations where symptoms are confusing, symptoms are too vague, or symptoms are caused by multiple problems.

The multiplicity of information sources consulted can make troubleshooting difficult, especially when the sources of information are not completely compatible. This incompatibility occurs when all information sources are not updated to reflect changes to the equipment (such as documentation that is out-of-date) and when information sources use different data formats (and the troubleshooter must do mental translations to relate the data). A number of managerial changes were suggested as ways to open channels of communication and ease other problems associated with troubleshooting. Training was also mentioned as in need of change, in terms of when it takes place, what it involves, and who gets it. There were also indications that the design of the

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