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Lower Level Repair Can Easily Fail Due to High Complexity

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The International Space Station (ISS) uses Orbital Replacement Units (ORU's) to repair failures on orbit. Using ORU's reduces the crew time required to repair failures, but several copies of each ORU must be stored on ISS to ensure system availability. A typical ORU contains many components and has significant mass, but each ORU can repair only a single component failure. A full set of the ORU internal components could repair many different failures. Lower level assembly or component repair should reduce total spares mass. Successful electronics repair experiments were conducted on ISS. However, implementing component level repair would require a significant effort. The systems must be designed so they can be repaired during a mission, considering component layout and accessibility. The repair procedures must be developed and repair facilities, tools, and diagnostic and test instruments provided. Tracing a fault to a component is much more difficult than isolating it to an ORU. Replacing a component is much more difficult than replacing an ORU.

Some problems with lower level repair are discussed. The mass savings of lower level repair will not save as much launch cost as before since launch cost has recently been reduced by an order of magnitude. Most system failures are not component failures that can be fixed by replacing a component but are due to system level problems. Repair and maintenance should be planned as part of an overall maintainability design. The risk that a lower level repair will fail is considerably greater than when using ORUs. With modern high reliability packaged systems, failure diagnosis and repair has become a lost art. However, diagnosis and repair data from the 1960's show that increasing complexity often causes much longer diagnosis and repair times and may prevent successful repair. Increasing complexity by using lower level repair directly increases system cost, failure rate, crew time for repair, and the risk of an unrepairable system failure.

Nomenclature

a = the rate of change of diagnostic time (Wohl model)
ECLSS = Environmental Control and Life Support System
I = system complexity index (Wohl model)
ISS = International Space Station
LLRU = Lower Line Replaceable Unit
LORA = Level of Repair Analysis
LRU = Line Replaceable Unit
MTBF = Mean Time Before Failure
MTTR = Mean Time To Repair
MU = Maintenance Unit
ORU = Orbital Replacement Unit
Pr(LOC) = Probability of Loss of Crew
R&M = Reliability and Maintainability
SRU = Shop Replaceable Unit
SCM = System Complexity Metric

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I. Introduction

LOWER level repair has long been suggested as a way to reduce spares logistics for space missions. This paper reviews the definition of lower level repair and quotes a paper explaining NASA's understanding of lower level repair. NASA's Component-Level Electronics-Assembly Repair (CLEAR) project is reviewed. Current efforts to implement lower level repair in systems similar to the International Space Station (ISS) life support are described. Some problems with lower level repair are discussed, especially risk. With modern high reliability integrated systems, failure diagnosis and repair has become a lost art. However, Wohl and others have reported and modeled useful diagnosis and repair data from the 1960's. Increasing complexity causes much longer diagnosis and repair times and may prevent successful repair.

A. The Line Replaceable Unit (LRU) and Lower Line Replaceable Unit (LLRU)

A Line Replaceable Unit (LRU) is an enclosed element containing integrated avionics circuitry that can be quickly replaced as a whole in the field if it fails. For instance, an aircraft radio LRU would be a chassis containing a power supply, radio frequency receiver, intermediate frequency tuner, amplifier, data interface, and audio output. An LRU is designed to be tested and replaced as a unit using little equipment and few tools. A failed LRU is usually returned to a depot or the manufacturer for repair.

LRUs have been used for many decades, but the use of lower level repair has often been suggested to reduce the procurement and storage costs of LRUs and to shorten the repair turnaround time. A Lower Line Replaceable Unit (LLRU) "is part of an LRU, and which can be removed and replaced at the field level to restore its LRU to an operational ready condition."[1] LLRUs can be subassemblies, modules, and even simple components or parts.

Level of Repair Analysis (LORA) determines where a system or its LRUs will be replaced, repaired, or discarded to achieve the required operational availability at the least life cycle cost. Repair can occur in the field operations locations, at intermediate repair centers, or at a depot or the manufacturer. At an operations location, a system or its LRUs can be removed and replaced or they can be repaired using LLRUs. LORA considers the costs of the LRUs or LLRUs and all the elements required to make the system operational, such as repair facilities, test equipment, personnel, training, crew time, and repair time as well as the cost to design and demonstrate the maintenance and repair approach.[2]

B. NASA's Understanding of Lower Level Repair

A discussion of the supportability challenges of human spaceflight considered the level of repair. It noted that,

> "(T)he ISS supportability strategy was specifically designed to minimize crew time spent on maintenance and repair by packaging components into ORUs. (ORU is the NASA term for LRU.) This approach saves crew time by simplifying maintenance and repair activities, but it also increases logistics mass… When ORUs are used, each spare part replacement removes not only the specific item that failed, but also any other items packaged within the same ORU. …Implementing repair at a lower level is a commonly-discussed supportability strategy that can enable more efficient maintenance and repair logistics, thereby reducing logistics mass; however, it also tends to have the effect of increasing the amount of crew time necessary for maintenance and repair activities."[3]

And importantly, "there is also a risk that a cluster of maintenance demands may overwhelm the crew's maintenance capacity, especially for critical systems. When a critical system such as ECLSS fails, there is a limited time to perform maintenance before the loss of functionality results in (Loss of Mission or Crew)."[3]

Lower level repair has benefits and costs.

> "(L)ower-level repair can result in significant reductions in spares mass requirements. Lower-level repair is more mass-efficient; for example, when maintenance actions can be executed at the component rather than assembly level, all other components within the assembly that are still functioning can remain in service and the mass of elements that are replaced is lower than it would be in a higher-level repair paradigm. …However, lower level repair can increase the complexity of system development and maintenance operations. In order to enable effective lower-level repair, systems must be designed to enable access to lower-level components, rather than collecting components into convenient boxes. Design for maintainability will place additional constraints on the physical design of the system from the perspective of crew access, tool clearances, potential hazards (sharp edges, containment for toxic materials, etc.), and sensing requirements for diagnostics. Crews must have the knowledge and tools to execute maintenance activities at a lower level, including diagnostic of system failures to identify failed components and removal/installation of those components. There may be additional risk to the crew during more complex maintenance operations, as well as an increased risk of unsuccessful maintenance. Increased complexity is also likely to increase the amount of crew time required for maintenance, just as reduced complexity resulting from the implementation of higher-level maintenance using ORUs is intended to reduce maintenance crew time. Decisions regarding level of repair must carefully balance their impact on logistics mass, crew time, and the challenges of design for lower-level maintenance."[3]

The benefit of lower level repair is reducing the mass of spares while the costs include increased complexity, greater cost for design and maintenance, the need for more crew time, and an increased risk of a failure to repair resulting in a higher Probability of Loss of Crew (Pr(LOC)).

II. NASA Lower Level Repair

NASA work on lower level repair includes the Component-Level Electronics-Assembly Repair (CLEAR) project and also developing a component level repair approach to prepare ISS life support systems for deep space.

A. The NASA CLEAR Project for Lower Level Repair

The Component-Level Electronics-Assembly Repair (CLEAR) project was conducted under the Constellation program from 2006 until Constellation ended in 2009. The lead scientists and engineers were Peter Struk of the NASA Glenn Research Center and Richard Pettegrew and John Easton of the National Center for Space Exploration Research. They published many significant contributions which are summarized here. [4, 5, 6, 7, 8, 9, 10]

The CLEAR project goals were "1) develop and demonstrate a manually-operated electronics repair capability to be conducted in a spacecraft environment; and 2) develop guidelines for designs of electronics that facilitates component-level repair for future space exploration efforts."[6] Initially the CLEAR project strongly expressed the need for lower level repair. "Severe limitations on mass and volume available for spares on long-duration spaceflight missions will require electronics repair to be conducted at the component level." "(C)omponent-level repair is clearly the pragmatic choice for deep-space missions, since the cost of bringing sufficient spare ORUs is great and the safety of the crew and mission cannot be compromised."[4]

Consideration of lower level electronics repair emphasized the need to consider system design, diagnostics, the tools and equipment needed to perform the repairs, the logistics of the spares stores, and crew factors.[5] Lower-level repairs include both replacement of LLRUs or Shop Replaceable Units (SRUs) such as circuit boards and repairing a SRU circuit board at the component-level.[8] In planning for component level electronics repair, system designers must consider the accessibility of components, the types of LRUs, LLRUs, and components to be repaired, diagnostic and test capabilities, tools and hardware required, and crew skill level and training.[9]

The CLEAR program recognized that electronics repairs require a broad range of diagnostic capability to isolate the faulty components and that manual repair has its limitations and is impossible for some highly integrated devices.[7] A CLEAR study of ISS operational experience found 42 percent of on-orbit electrical problems could be handled using component-level repair. "Problems that would not benefit from a component-level repair capability stem from software, operations, or documentation errors."[8]

An ISS life cycle cost model for ten years of operation found that replacing ORU maintenance by LLRU or SRU level replacement reduced cost by 82 percent. Adding component level repair reduced life cycle cost by another 2 percent, for a total of 84 percent. The model included crew time. Relative to ORU replacement, SRU-level replacement increased crew time by 28 percent and component-level repair of the SRUs increased crew time by 51 percent.[5] "The CLEAR team recommended the development of semi-automated or automated devices with assistance from ground controllers to help conduct diagnostics, repair, and post-repair testing." [9, 8]

An ISS component level repair experiment "provided two-layer, functional circuit boards and replacement components, a small tool kit, written and video training materials, and 1 hr of hands on training for the crew."[10] The astronauts replaced some components successfully but also were unsuccessful on several tasks. Needed process improvements included more and better training closer to the mission, on-board video training and practice, and more and better hand tools.[10]

Completely eliminating LRU replacement is not practical. "Finally, the authors recommend a mix of replacing entire LRUs when the system is a critical component, having spare circuit boards for circuits requiring complex repair techniques, and spare components for LRUs that are not mission critical and do not require difficult repair procedures." [5]

Research for a planned Chinese space station by the Chinese Academy of Sciences summarized and endorsed the NASA CLEAR project recommendations. The paper noted that Russia in Mir used complete replacement only for the key ORUs and did internal maintenance for most of the ORUs.[11]

B. NASA Collins Component Level Repair for Deep Space

In a continuation of a NASA program to develop the ISS Environmental Control and Life Support System (ECLSS) hardware systems for deep space, Collins Aerospace has developed an in-flight maintenance approach using lower level repair. The first step identified assemblies that should be designed for removal from the overall system for maintenance. These Maintenance Units (MUs) are specifically designed for in-flight maintenance. They will be removed from the system, taken to a workbench, repaired by replacing components, and then returned to the system. Collins found that a maintainable design could not be achieved by simply designing the components for removal and replacement, since this resulted in increased weight, volume, complexity, and cost.[12]

A key enabler for component level repair is the ability to isolate faults at the component level. An Intelligent System is being developed to do this. Repairing faults at the component level will drastically reduce the launch mass of spares compared to the ISS approach of replacing ORUs.[13]

C. Problems with Lower Level Repair

The idea of using lower level repair raises some questions that are considered below. The most significant is that lower level repair may be unsuccessful, which increases risk for the crew.

1. *What is the intended lower level repair approach?*

The ISS uses replaceable ORUs for all systems. The ORUs are not intended to be repaired on board. Collins suggests using ECLSS MUs designed for in-flight repair. CLEAR recommended that electronics use a mix of replaceable ORUs/LRUs, replaceable LLRUs/SRUs such as spare circuit boards, and also spare components for circuit boards.

2. *How is the best lower level repair approach to be determined?*

Cost-benefit analysis is needed. The cost metric should probably be the mission life cycle cost, including systems, spares, equipment, and support. The hardware mass is a poor indicator of mission cost, since the launch cost to orbit has been greatly reduced in the last few years. The new low launch cost also weakens the most direct argument supporting lower level repair, that it reduces spares mass. The crew time needed to repair systems has been a burden on ISS, especially for ECLSS, but crew time is difficult to estimate or control and is subject to emergency demands. Using up-time, availability, or Mean Time To Repair (MTTR) as goals assumes normal operation without crises. This ignores the essential problem of surprising and difficult to diagnose failures. The objective of ECLSS maintenance and repair should be to reduce the Probability of Loss of Crew [Pr(LOC)] to an understood and acceptable level.

3. *Most system failures are not component failures.*

CLEAR found that failures were caused by "software, operations, or documentation errors." To this can be added errors in requirements, design, and manufacturing and unexpected space environment challenges. CLEAR found that 40 percent of failures were caused by components, but a more typical value is only 20 percent.[14]

Component level repair can address only a small portion of the system failures. Complicated multiyear ECLSS trouble shooting efforts on ISS confirm that the most difficult failures to analyze are system level failures, not components. The usually accepted idea that sufficient spare parts can get us safely to Mars is wrong.[15]

4. *The failure repair method should be part of the overall reliability and maintainability design*

The recent NASA technical standard on Reliability and Maintainability (R&M) requires projects to start by developing the R&M requirements and the strategies to implement them. This assumes the full system engineering design and development process will be carried out and be coordinated with risk management, safety, security, quality assurance, logistics, probabilistic risk assessment, life-cycle cost, and configuration management. This approach is intended to ensure that R&M is designed in from the beginning rather than added with difficulty to an already completed design concept.[16]

5. *The key issue is risk*

A deep space mission must keep all its vital systems operating using on board spares and capabilities. An unrepairable failure of a vital system can cause loss of crew. Identifying and eliminating risk is difficult, and it rapidly becomes much more difficult as the complexity of the system and the repair approach increases.

D. Failure diagnosis and repair has become a lost art

As the CLEAR program noted, modern electronics is reliable, tightly packaged, and inexpensive. Unlike the electronics of the 1960's, it is not worth trouble shooting and repairing. There are now very few experienced electronics trouble shooters, which was a problem for CLEAR. It was very surprising to read of ISS astronauts in the CLEAR program being taught soldering and working on printed circuit boards. However, in the 1960's this author did the same. I was the only trouble shooter for the Sargent missile radar fuse for several years and also did failure analysis for the Sidewinder missile and supporting ground equipment and test gear. I learned things about trouble shooting that have been forgotten by the current engineering culture.

Most problems are easy to solve but some are very hard. Failures are easy to diagnose when basic engineering knowledge and standard trouble shooting procedures are sufficient. But sometimes failures are baffling and seem inexplicable. The standard model of the system used to predict its behavior simply fails. Some examples I recall are solder flows making weak connections under circuit boards, internal radio frequency interference, improper grounding, power line noise, and many cases of intermittent or drifting performance. We would complain of malevolent gremlins bent on sabotage. The common thread is the appearance of a new unexpected factor that produces surprising behavior. Easy problems are solved using common knowledge, but hard problems require thinking outside the box, going beyond the usually correct system behavior assumptions. Basic trouble shooting for easy problems can be taught, even made into a procedure and programmed. The methodology for hard problem solving is explainable only in general, since it requires doubting what you know and exploring alternate realities. Some problems cannot be solved by the troubleshooters on hand in the time available.

III. The Wohl Repair Time Data and Model

Trouble shooting, diagnostics, and repair time prediction were major concerns in the 1960's and 1970's and extensive research was conducted. This work presents and explains the data on repair times and suggests that occasional inability to diagnose a failure is due to human cognitive limitations in handling complexity.

A. Wohl investigated excessively long repair times

Joseph Whol with MITRE and later ALPHATECH extensively analyzed 1960's data on several thousand repairs of different kinds of electronics equipment. He reported the results in the early 1980's. [17] [18] [19] [20] Wohl was especially interested in understanding the required repair time and the varying difficulty in the electronic troubleshooting process. There were surprising differences in repair times between laboratory demonstrations and actual field repairs. Repair times under laboratory conditions were exponentially distributed but the same equipment under field conditions often had much longer repair times.[17]

The Weibull cumulative distribution has the form F(t) = 1 – EXP [-(t/a)^b], where a is the time scale parameter and b is the shape parameter. For b = 1, the Weibull distribution reduces to the exponential. The laboratory repair time distribution data had b ~ 1 and was nearly exponential, while the field data for longer repair times had b ~ 0.5, reflecting a much larger probability of longer repair times.[17] Figure 1 shows representative field data on the percent of repairs completed versus repair time with an exponential distribution for comparison.

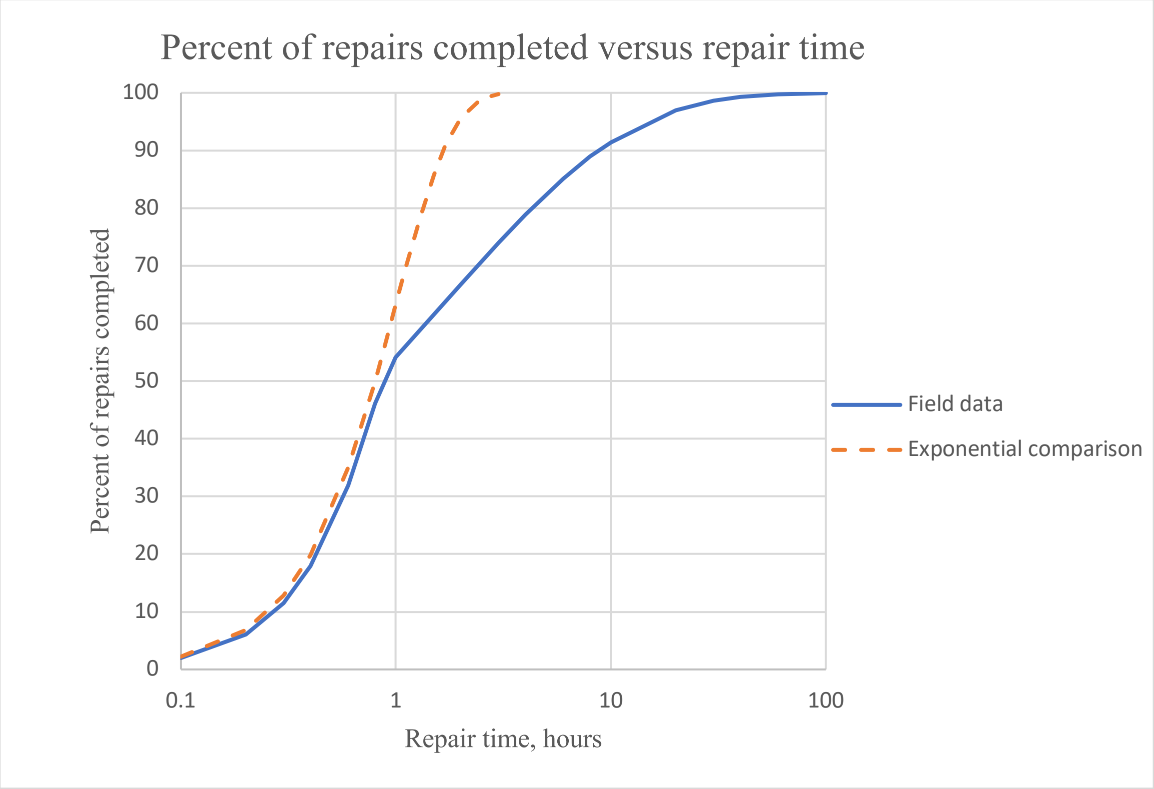

Figure 1. Percent of repairs completed versus repair time for field data and an exponential comparison.[18]

The field data of Figure 1 is based on Figure 3 of Wohl, 1982,[18] which is one of ten similar plots of field repair data. Initially, the field data percentage of repairs completed increases slightly faster than exponentially, with b = 1.065. For repair times longer than about one hour the field diagnosis process drastically changes. The repair time increases significantly, almost without limit, corresponding to a cumulative Weibull distribution with b = 0.5. The field repairs which take longer than an hour or two may take tens of hours, far exceeding the repair times predicted by the exponential distribution. This appeared to be due to much greater difficulty in fault diagnosis. This may be due to the unfamiliar and complex failure modes that can occur in complex systems. Figure 2 shows the probability distributions of the field repair times, rather than the cumulative distributions in Figure 1.

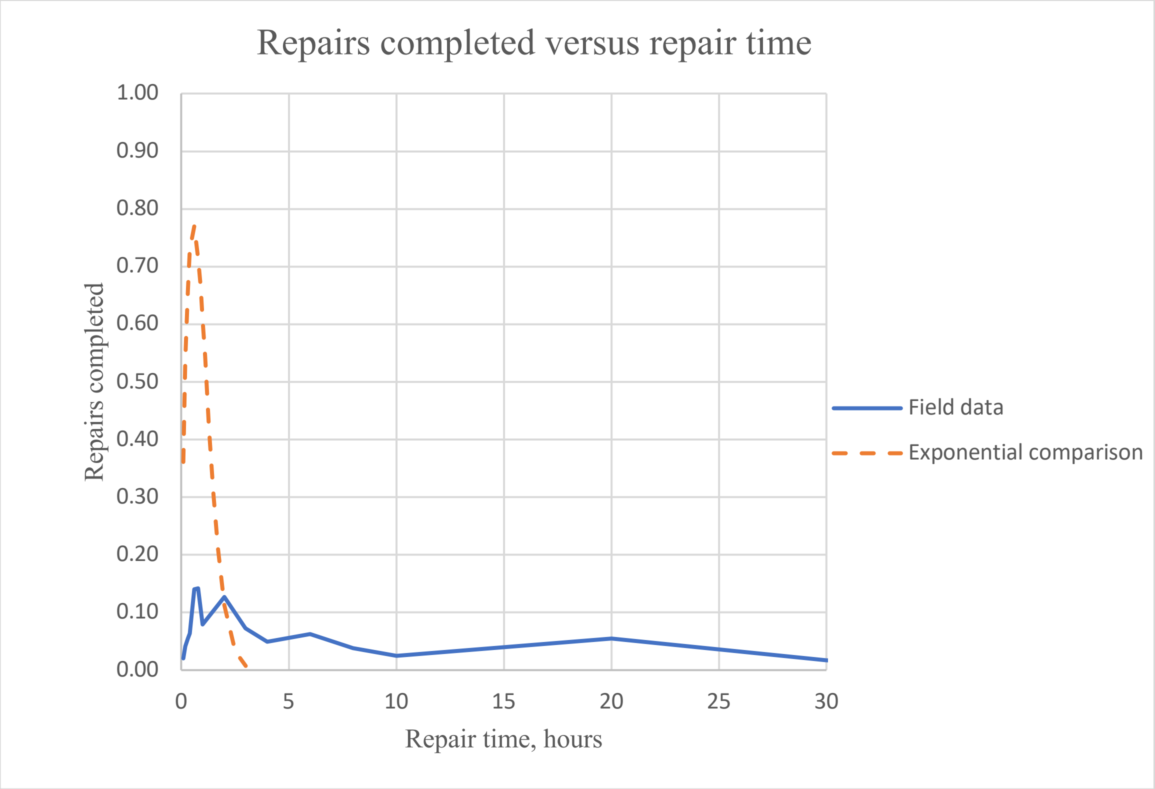

Figure 2. The probability distribution of the field data repair times and an exponential comparison.[18]

Figure 2 makes it clear that an exponential distribution would predict that nearly all repairs would be completed in a few hours, while the field data corresponding to a Weibull distribution with b = 0.5 has a “long tail,” corresponding to a larger than expected probability of extreme events, in this case very long repair times.[18]

Figure 1 is the cumulative distribution as time increases of all repairs. This is the percentage of repairs completed in less than the given repair time. The Figure 1 field data shows 54% of repairs are completed within one hour and 92 % are completed by ten hours. Most repairs take much less time to finish.

Figure 2 shows that 7.9% of repairs fit in a time slot around 1 hour and 2.5% of repairs take in the neighborhood of 10 hours. Figure 2 shows the percent of repairs that take approximately the given repair time.

Because of the long tail of the field repair time in Figure 2, the average repair time tends to be dominated by a few very large repair times. The average repair time, corresponding to the mean of the Weibull distribution, is proportional to (1/b) factorial, and can become very large for small b. Experience confirms that some repairs take very long or are never accomplished, so that for some systems the actual average repair time is infinite. This suggests that component level repair of complex systems may be too risky for deep space missions.

Most analysis and discussion of expected repair times emphasizes the easy and routine problem solving represented by the exponential distribution. This fails to correctly predict field repair times. Fault diagnosis or troubleshooting takes most of the repair time and is very variable. This should be considered in system design and in repair and maintenance planning. It seems clear that the many long repair times are due to diagnostic difficulty, and that this seems to be related to system complexity. Two further observations support this. In the laboratory studies of repair times where the failures modes were imagined and deliberately introduced into the system, the repair times were exponentially distributed. The failure modes that can be imagined are easily diagnosed using routine problem solving. Not so for field failures. Even the same equipment that showed the shorter exponentially distributed repair times in the laboratory showed the unexpected longer repair times in the field.

B. The Whol model to predict average repair time

Wohl developed a data-based model to predict average repair time based on system design features. He used nine sets of field data and three sets of laboratory data described in Table 1 of Wohl, 1982.[18] The function he modeled was the average repair time, which varied from 2 to 6 hours for field data and from 2 to 25 minutes for laboratory data. The next measured data variable was t0, the average time to perform a diagnostic test, which depended on system design and test location. t0 was typically 15 to 30 minutes in the field but only 2 to 8 minutes in the laboratory. The key data element was a system complexity index, I, equal to the average number of items directly connected to any one item, where the items were "components, modules, circuit boards, etc."

It seems reasonable that the parameters t0 and I will influence and can help predict a system's average repair time. A complex mixed polynomial and logarithmic equation was developed to estimate average repair time. The equation's form and parameters were adjusted to visually best fit the data. In order to predict the long average repair times in the field data, it was necessary to assume that, after each test, the time needed to perform the next test increased. That is, the time to perform the first test was t0 but the time to perform the nth test would be tn.

$$\mathrm{tn} = \frac{\mathrm{t0}}{\mathrm{a}^{\mathrm{n}-1}}$$

The parameter "a," a < 1, represents the rate of increase of diagnostic time with each step.

The trouble shooting process tends to decelerate, since it seems logical to work on the most accessible components first, to do the easiest and most informative tests first, and then to find it increasingly difficult to interpret the observed symptoms and test results as more are accumulated.

The parameter "a" defines the geometric growth of test time during diagnostics. For the laboratory data, a = 1, corresponding to the exponential distribution of repair times. For the field data, test time growth parameter "a" had a surprisingly narrow range, 0.85 < a < 0.90, with an average value of a = 0.867.[20] The measured and predicted values of average repair time for field data are shown Figure 3.

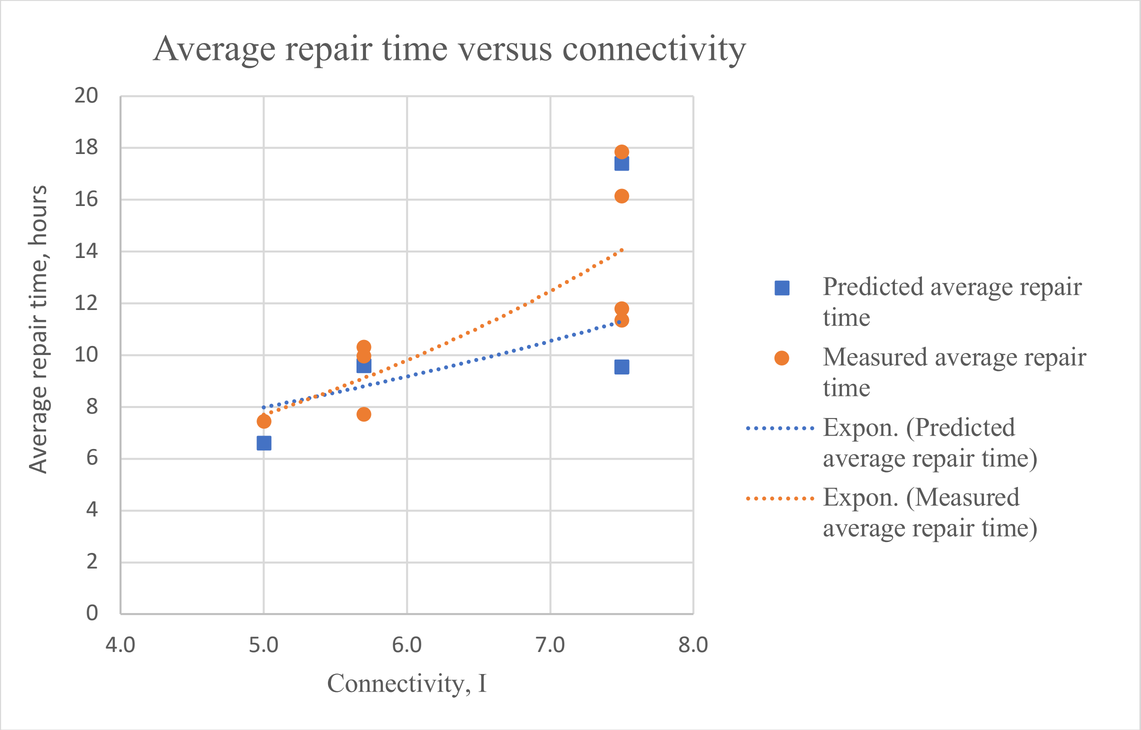

Figure 3. The measured and model predicted values of average repair time for field data.

The data plotted in Figure 3 are taken from Table 1 of Wohl, 1982.[18] The measured and predicted average repair times in the table were divided by their respective system t0, since the predicted average repair time is directly proportional to t0.

The model suggests several interesting results. First, the Wohl model shows higher repair times are associated with, and presumably caused by, higher system complexity. When the complexity index, I, increases from 5 to 7.5, average repair time increases from 7 to 14 hours. The repair time increase is proportionally larger than the complexity index increase and evidence below suggests that it may increase exponentially. Second, the complexity index, I, is bounded between 5 and 7.5. Wohl suggests that this can be a reflection of the frequently noted limit on the human ability to deal with complexity. He cites the foundational 1956 paper by Miller, titled, "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information."[21] It appears that human data discrimination and short term memory are limited to about seven items. Systems designed by humans must be understood by humans, so their complexity is constrained by this limit on human cognition. Third, the longer field repair times and the geometric growth of repair times seem due to a special class of rare failure modes. He mentions accidental shorts due to loose wire pieces or solder flows, spills of coffee or other liquids creating a high resistance leakage connection between components, and a loose ground connection creating a floating ground. To these can be added internal radio frequency coupling, intermittent connections opening and closing with temperature, and many more unexpected failure modes. While isolated component failures simplify the failed system, this difficult class of failure modes adds a new connection that makes the system more complex and more difficult to diagnose. This means that the system fails to operate according to the system schematic with a component removed, as is common and usually initially assumed. Fourth and finally, the model indicates that if the complexity index, I, becomes large enough, so that $[(I - 1) / I] > a$, where "a" is the test time growth parameter, the average time to repair becomes infinite. Rearranging this equation, the average repair time becomes infinite if $I > 1/(1 - a)$. Using the average value of $a = 0.867$, the average repair time becomes infinite if $I > 7.5$. Using the highest value of $a = 0.90$ for field data, the average repair time becomes infinite if $I > 10$. If $a = 1.0$ as for laboratory data, the complexity index, I, must become infinite before the average repair time becomes infinite.

If systems become more complex, this increases the probability that complex failure modes will be difficult or even impossible to diagnose and repair. The obvious method to reduce the complexity of repair is to modularize the system and provide easy diagnostics and higher level LRUs. This is done in the ISS ECLSS, but even so there have been many complex and difficult to diagnose system level problems. Abandoning ORUs to use lower level or component repair greatly increases the risk that some failure problems will be extremely difficult or even impossible to diagnose.

IV. Other Empirical Research in Troubleshooting

Rouse and coauthors reviewed empirical research in troubleshooting. Morris and Rouse prepared a "Review and evaluation of empirical research in troubleshooting" in 1985 which included nine references to Rouse's previous publications.[22] They found that troubleshooting performance can be impaired due to the size and complexity of the system. Increasing the number of components in a troubleshooting task results in more diagnostic errors. The amount of time to solve problems depended on the number of functional relationships to be considered. Feedback loops also create problems for troubleshooters. Surprisingly, training in the theories and fundamentals is helpful in answering theoretical questions but no use in solving problems. Theoretical instruction is simply ineffective in developing good troubleshooters.[23]

Rouse was not surprised to find that troubleshooting performance declined as problem size increased. And, "increased complexity presents problems when the equipment fails since trouble-shooting or fault diagnosis becomes a task too complicated for the human to perform." One obstacle to diagnosis was that humans have considerable difficulty in accepting and using information that contradicts their current working theory.[24]

The literature often identifies system size and the connectivity between components as metrics of system complexity. In a large highly connected system, it is difficult to understand the relations among system components, which leads to increased difficulty in failure detection due to the human limit on information processing. Much work tries to define and estimate complexity to predict such things as cost, failure rate, and mean time to repair.

V. Conclusion

It is clear that using lower level repair will increase cost for system design and test, crew training time, crew time for repair in space, and create a risk that some repairs will be too difficult to accomplish. It seems surprising that NASA plans to implement lower repair in space without considering its increased cost and reduced safety. The justification for lower level repair is that it reduces the mass of spares, but minimizing mass is unimportant compared to reducing cost and increasing safety. Recently launch cost has been reduced by a factor of 10 or 20 and mass is no longer a major cost driver. Some of the support for lower level repair is based on the false assumption that most system failures are caused by component failures and so can be cured by replacing components.

Life support seems to be guided by the vision of a future closed human ecosystem independent of Earth. This promotes the concepts of increasing closure, reducing launch mass, recycling even minor and difficult wastes, and performing repairs on board. However, near term missions will be completely different and entirely dependent on logistics materials supplied from Earth and stored. Providing cost-efficient and reliable life support will not require increasing closure, reducing launch mass, recycling minor difficult wastes, or doing repairs on board. It is more likely to be impaired by them.

The advocacy of lower level repair violates the three most fundamental rules of systems design:

1. Simplify, simplify, simplify
2. Keep It Simple, Stupid (KISS)
3. Murphy's Law: If anything can go wrong, it will go wrong.[25]

Complexity is the enemy, the opposite of simplicity and good systems engineering. Complexity can easily be measured and quantified. Wohl used a system complexity index equal to the average number of items directly connected to any one item. Jones developed a System Complexity Metric (SCM) equal to the sum of the number of nodes in the system plus the number of one-way interactions between the nodes.[26] These measures of complexity are simple to compute and are good predictors of cost, failure rate, repair time, and the probability that a failure cannot be repaired. Reducing complexity directly reduces cost, failure rate, crew time for repair, and the risk of an unrepairable system failure.

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