Automatic Generation of a Diagnostic Expert System from Failure Mode and Effects Analysis (FMEA) Information

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ABSTRACT

This paper describes a project to convert the results of Failure Mode and Effects Analysis (FMEA) information into a diagnostic knowledge base. Combined with a diagnostic expert system, this knowledge base produced an effective diagnostic system for an off-highway vehicle.

The paper delineates how FMEA data elements were used in the construction of the diagnostic knowledge base, and the significant performance improvement that resulted from its use as compared with traditional service information tools.

Future work to improve the diagnostic development process is discussed, and how the methods described herein can be used to improve the overall FMEA process.

INTRODUCTION

It is an unfortunate reality that the availability of adequate diagnostic capabilities often lags behind the introduction of a new machine. This is a result of the inherent difficulty in producing sufficiently reliable information about field failures, especially as the complexity of machines increases simultaneously with the costs of producing the diagnostic capabilities for it.

When designing any diagnostic system, whether a hard-copy service manual, or an elaborate troubleshooting expert system, models of device failures are used to trace the root-cause of system and component failures.

Failure Mode and Effects Analysis (FMEA) is a design discipline and a quality-planning tool used to investigate the sources and the consequences of failures on the operation of a system. The purpose of the analysis is to highlight any significant problems with a design, and, if feasible, to modify the design to avoid those problems.

FMEA is a systematic and analytical process that combines top-down and bottom-up analysis. From the top, the system functional goals are decomposed into sub-system goals and, from the bottom, the component behaviors are expressed as the functions required to realize the goals of each sub-system. Failure modes are then defined, and the resulting behavioral changes are classified according to their effect on goal achievement.

Similar to the diagnostic authoring process, FMEA decomposes the system under investigation into its elementary components and their failure modes, as well as calling out the symptoms (effects) of these failure modes. Therefore, capitalizing on the qualitative and quantitative characteristics of FMEA for diagnosis purposes seems intuitive.

In practice, however, the typical use of FMEA is only as a secondary source of ideas for the types of faults that might occur, and the challenge of exploiting FMEA data as input for diagnostic system development is a long-standing one. Efforts have been made to convert FMEA results into a diagnostic knowledge base, most notably by Price et al. [1]. However, most of these efforts have been limited to small subsystems – often simple electrical circuits – were very resource intensive, and only a few have advanced beyond the academic arena to become tools for general use. At the same time, some of these projects were very aggressive, attempting to programmatically perform FMEA directly from CAD systems, potentially rendering them too complex for an industrial environment.

THE EXPERT SYSTEM

The expert system used in this project is an off-the-shelf model-based expert system, designed solely for diagnostics. The system is architectured as a blackboard [2] for shallow causal modeling. It a truth-maintenance system [3] and uses Bayesian probability calculations [4] to generate a very robust cost-effective troubleshooting strategy, and requires very few external controls to guide it. Even a shallow knowledge representation results in an effective diagnostic system. This is a critically important characteristic as FMEA itself does not describe the diagnostic properties of the machine, nor does it prescribe the analytical diagnostic process to isolate the various failure modes down to root causes.

Additional features of the system allowed the effort to focus on diagnostic representation rather than on programming complex software, which often becomes the prime impediment in implementing expert systems in an industrial environment.

Knowledge acquisition does not involve traditional programming. Instead, a feature-rich graphical user interface allows domain experts to interact directly with the authoring environment using their own nomenclature and practice.

- Facilities to import data from external sources directly into the knowledge base.
- Ability to modify the diagnostic behavior using simple diagnostic-driven methods. This capability is vital, as the diagnostic system should be able to respond to considerations that extend beyond pure FMEA, such as part costs and warranty policies.
- An extensive knowledge proofing environment.
- Facilities to embed the expert system engine in the runtime environment.

KNOWLEDGE REPRESENTATION – Although the full repertoire of knowledge representation expressions is very rich, only a small number of knowledge sources are mandatory, supporting a straightforward and easy to understand knowledge representation:

Component Objects – represent field replaceable units and potential failure modes. They also represent failures such as environmental conditions and operator errors.

Symptom Objects – represent indicators of malfunction exhibited by the machine (e.g. service codes) or reported by the operator (e.g. functional degradation). Symptom and component objects are linked through a probability-based association.

Repair Objects – are activity objects that can alter the state of component objects, i.e. remedy them. Repair objects account for part replacements, adjustments, correcting operator errors, and so forth. Repair objects carry various cost attributes that are used by the expert system to devise cost-conscious diagnosis.

Test Objects – are activity objects that obtain information and reason about the state of component objects. Test objects represent machine tests, measurements and observations. Object attributes express the diagnostic evidence extracted by the testing activity, as well as the time and effort for acquiring it.

FMEA DATA REPRESENTATION – Figure 1 shows a fragment of an FMEA worksheet of an electronically controlled transmission. FMEA is a very structured process, and a standard FMEA worksheet includes a number of administrative fields designed to facilitate workflow and lifecycle management. As these data elements do not play a role in diagnostics they were omitted from the table.

Failure Modes – are the anticipated ways in which a system or a component will fail, preventing it from accomplishing its designed goal.

Failure Effects – describe the performance impact on the system or service, and the effects of failing components on each other.

Causes – describe the potential reasons and causes for the described failure mode.

Occurrence – is the likelihood that the Failure Mode will occur over the design life of the system. Combined with **Failure Severity** and **Detection**, FMEA classifies and quantifies failure effects using an overall risk and priority rating (**RPN**).

The FMEA information was converted to the Diagnostic FMEA worksheet depicted in Figure 2. (The table was reformatted and some data elements were omitted.)

Item Functions	Potential Failure Mode	Potential Failure Effect(s)	Sev	Potential Cause(s)/ Failure Mechanism(s)	Occur	Detec	RPN
P2-A02 / +5V output power to Rotary Sensor	Open Circuit	Won't shift out of neutral. If in Forward, when fault is detected, reverts to neutral.	8	Broken wire Connector not properly assembled Contamination/moisture in connector No signal from controller A02 Open circuit in sensor	2	3	48
	Intermittent Open Circuit	Accelerates/decelerates at frequency of intermittence.	8	Broken wire Connector not properly assembled Contamination/moisture in connector	2	3	48

Figure 1. FMEA Worksheet

IMPLEMENTATION – Standard FMEA does not include testability and maintainability information. This information was obtained from the necessary disparate sources and handcraft into the Diagnostic FMEA worksheet. Repair information was categorized two classes of activities: replacements and adjustments. Cost information was encoded using three classes, corresponding to the types of diagnostic activity: tests, adjustments, and replacements.

A knowledge base was implemented utilizing FMEA information of an air-conditioning system, an electronically controlled transmission, and a hydraulic system of an off-highway vehicle. Figure 3 shows the knowledge representation of the symptom "Vehicle wont shift out of neutral" from Figure 2. This representation generated the diagnosis logic tree depicted in Figures 4. Figure 5 shows the same symptom information displayed by the runtime environment.

| Symptom | Detection | | Cause | | | | P |
	Originating Unit	Activation	Component	Ref. Des.	Failure Mode	Cause	
Won't shift out of neutral	A02	Voltage < +1.5V	Harness	WHA02	Open Circuit	Broken wire	4
					Short to Ground	Pinched Wires	5
					Short to B+	Pinched Wires	5
			Connector	P2	Open	Bad assembly Contaminated	5
			Controller	A02	Short (Int.) Open (Int.)		2
			Sensor	S11	Short (Int.) Open (Int.)		2

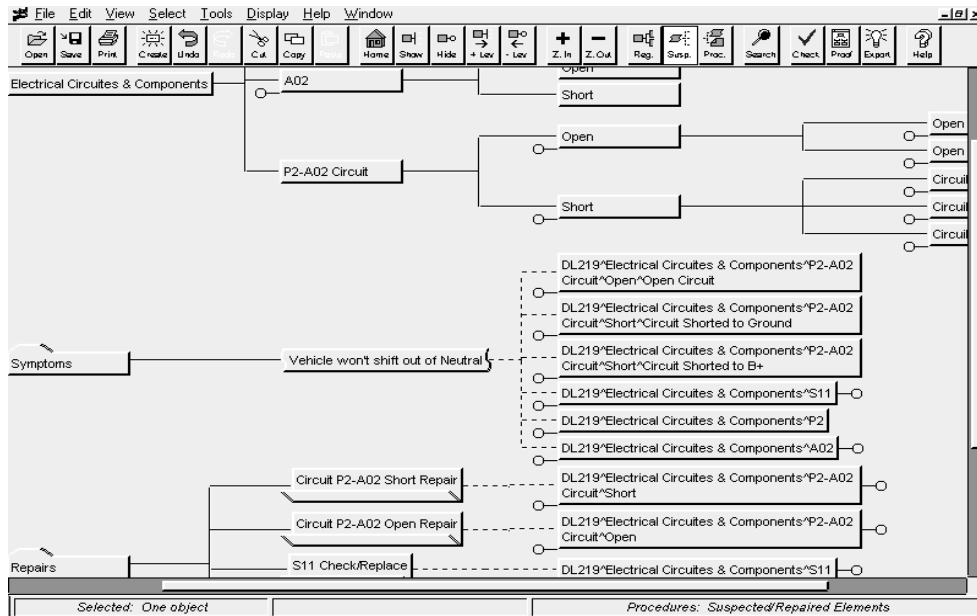Figure 2. Diagnostic FMEA Worksheet

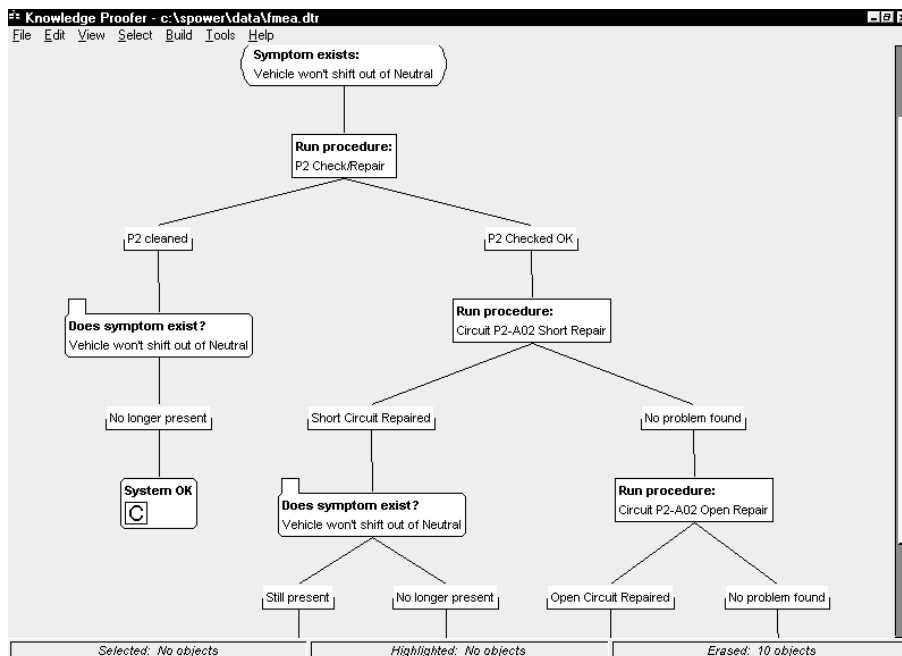Figure 3. Knowledge Representation
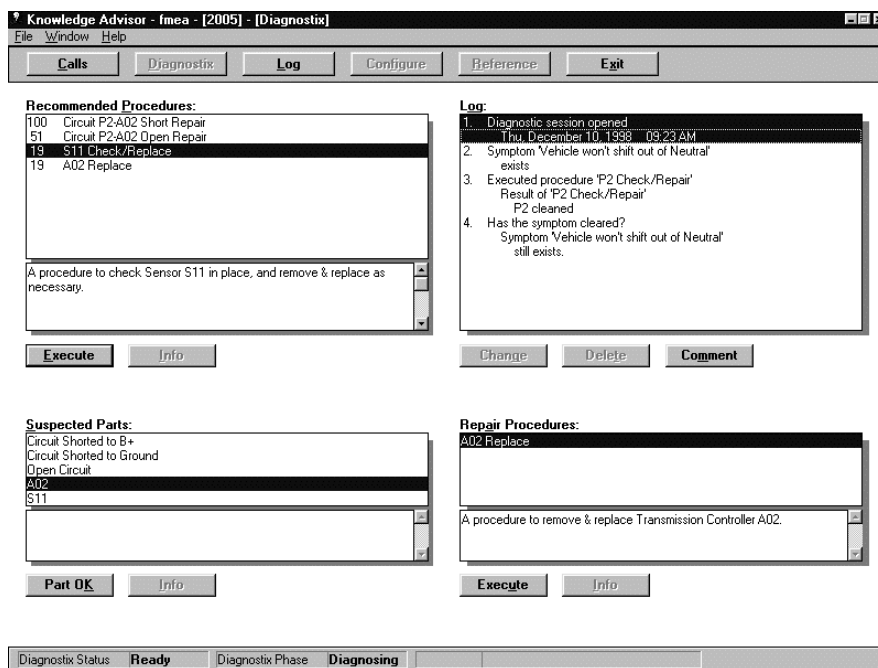
3

Figure 4. Diagnostic Logic Tree

Figure 5. Runtime Environment

RESULTS

In order to assess the performance of the knowledge base, technicians with varying levels of skills and experience used the expert system to troubleshoot actual faults induced in the machine in a configuration similar to the one depicted in Figure 5. Their performance was compared to the performance of technicians using the standard maintenance documentation. The test was conducted using double-blind methods.

HIT RATE – Hit rate is the percentage of diagnostic sessions in which the technician successfully troubleshot and repaired the problem, regardless of the time it took. As Table 1 shows, the average hit rate using the expert system was significantly better than using just the technical manuals. The expert system presented the technician with a focused and precise course of action, whereas, using the manuals, the technician had to device a troubleshooting strategy independently. Another outcome of the diagnostic precision of the expert system was a significant reduction in false part replacements.

Table 1.   Hit Rate

	Manuals	Expert System
Average	60.0%	90.0%
Level 1	44.4%	90.0%
Level 2	66.7%	90.0%

REPAIR TIME – As table 2 shows, the average repair time with the expert system was significantly shorter than when using the manuals alone. The expert system presented the technician with a cost-effective course of action that was more effective than used by the technician. As the expert system presented the technician only with the pertinent information, it saved time otherwise spend looking up information in the manuals.

Table 2.   Repair Time

	Documentation		Expert System	
	Average (min.)	Std. Dev.	Average (min.)	Std. Dev.
All	49:39	22:38	20:00	6:07
Level 1	57:30	25:00	23:00	6:00
Level 2	39:10	13:03	15:00	0:00

As expected, and as shown in Table 2, the initial standard deviation for the Level 2 technicians was significantly better - about half - of that of the less experienced technicians. Utilizing the expert system, the standard deviation has improved and became more uniform for both populations The difference in repair times between Level 1 and Level 2 technicians when using same diagnostic method stems probably from the fact that experienced technicians can perform the same procedure faster. It should be noted that while the expert system can shorten the "thinking" (diagnosis) time and minimize the number of redundant test and repair activities, it cannot affect the "hands-on" time. Consequently, the time improvement is always gated by the actual time spent on performing test and repair activities.

DISCUSSION

LIMITATIONS OF FMEA – One of the challenges in utilizing FMEA for field diagnosis is the fact that it deals primarily with design documents, conceptual models, and early prototypes, and focuses on design artifacts. FMEA assumes that, under ideal circumstances, all failure effects are addressed and fully rectified during the design and engineering phases. Field diagnosis, on the other hand, deals not only with design inadequacies, but also with physical variations and natural mortality stemming from aging on the one hand, and product modifications and improvements on the other. Consequently, the considerations involved in prioritizing the FMEA information –

except for safety considerations – are isolated from field service. As FMEA was originally conceived as an engineering discipline, it ignores the operational, logistical, and financial considerations of the field service operation, such as repair times, parts costs, inventories, and warranty policies.

Another limitation of FMEA is that it involves a significant level of guesswork and prediction, which can only be used as an approximation as to what may occur. Failure rates cannot be guaranteed to be accurate and are not stable because component failure probabilities will change depending on its manufactured quality and on how it is used. Moreover, typical FMEA sessions are conducted only early in the product lifecycle and, over time, if not updated periodically, lose their relevance.

A fundamental hurdle in devising an FMEA-based diagnostic system is its inability to capture sufficient testability and maintainability information to allow an expert system to conduct effective functional testing. During initial prototyping this concern was not critical, as the knowledge base was fully operational without tests, although a knowledge base that contains no tests (or tests with poor testing capabilities) will tend to exhibit a "shotgun" strategy - replace parts based on their failure probability costs.

These limitations have a significant impact on the ability to generate cost-effective, field-service centered troubleshooting strategy from FMEA. At the same time, it is important to note that pragmatically, not all information is required immediately, nor is it required to be complete or error-free. It is desired for accurate and optimized performance, but can be increased and enhanced over time.

As a discipline and a process, FMEA has significant limitations and its efficacy is sometimes questioned by organizations that struggle to justify the additional activity. As a result, the process and the results are often underutilized.

FMEA, by nature, is a very subjective process. The final result of an FMEA is not definitive but varies depending on the experience and knowledge the engineers applied. An FMEA engineer will often use different descriptions for different occurrences of exactly the same effect, or reuse the same description for two slightly different effects. This makes it difficult to collate all the faults which could manifest a particular set of symptoms.

FMEA is intended to highlight problems with a design. As such, the FMEA process may prompt changes to the design, necessitating repetition of the FMEA process. Performing FMEA as early as possible in the design cycle identifies potential problem areas at the time when design changes can be made at lower cost. Unfortunately, FMEA is often performed towards the end of the development cycle of a new device, rendering the potential remedial impact too late in the design cycle and too expensive.

OBJECT-ORIENTED FMEA – Managed manually, FMEA cannot be fully utilized because of inconsistencies in effect description. In order to address the limitations of hand-coded FMEA and the increased data requirements of an effective diagnostic system, we are investigating the implementation of an object-oriented FMEA environment and the use of FMEA object libraries.

Object-oriented FMEA implements methods that promote the reuse of existing information and discourage the authoring of information from scratch.

When a new design is investigated, it is important to look at failure modes of previous devices that are of similar design and have similar functions, features, or components. It is also desired to look at the same components that have been designed for the same purpose in order to explore failure modes that might apply to the new device.

An object-oriented approach allows the introduction of object libraries: testability and maintainability information stored as independent entities that can be associated with failures as needed. As new designs often reuse components for which testability and maintainability information already exists, the system will be able to suggest already known FMEA objects and their associations. As the engineer investigates a new failure mode, the following are available for consideration and reuse:

- Already encoded effects that will eliminate identical effects from being expressed differently, and ensure that identical failure modes are not duplicated.
- Each failure mode is automatically associated with the appropriate repair objects.
- Failure modes that are already associated with test objects are presented to determine if the test is relevant within the new context and modify the diagnostic evidence.

Object-oriented FMEA will allow experience to be collected and reflected over time, and to ensure a faster response to new models, physical changes, and other lifecycle requirements. As these are implemented and FMEA data is derived, the diagnostics knowledge base can be quickly modified to reflect the new change.

CONCLUSION

Using FMEA to produce diagnostic aids, we expect to see a significant improvement in diagnostic lifecycle costs. Capitalizing on the qualitative and quantitative FMEA analysis in an automated fashion allows for immediate reuse of information at a relatively small incremental cost, thereby improving time-to-market and cost reductions.

We also expect to improve the accuracy of the FMEA and lower the costs of keeping the data updated. In effect, we strive to make FMEA the common language to communicate diagnostic knowledge within the organization – primarily between Engineering and Field Service.

We believe that the use of an object-oriented approach can alleviate many of the limitations of FMEA, streamline the data collection and organization and encourage aggressive information reuse. Early FMEA should become part of the development process instead of a last minute check.

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