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Development and evaluation of the Maintenance Error Decision Aid (MEDA) process

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Abstract

The purpose of this study was to evaluate the development and implementation of an airline industry process for determining the factors that contribute to maintenance errors and making corrective actions to eliminate or reduce the probability of future, similar errors. A process like this is useful because maintenance errors have safety and economic consequences to the airline industry. The Maintenance Error Decision Aid (MEDA) process was developed based on the philosophy that maintenance technicians do not make errors on purpose, that errors result from a series of related contributing factors, and that these factors are largely under management control and, therefore, can be changed. The process was field tested by employees of eight airlines and one repair station. Five surveys, two meetings, and completed MEDA Results Forms were used to evaluate the process. Survey results indicated that: the MEDA process was easy to use, maintenance technicians did not feel intimidated by the process, and management and staff felt MEDA was useful and should be continued after the field test. Feedback from the meetings was that MEDA had been successfully used to correct contributing factors to error, and airline management commitment was the most important factor for successful MEDA implementation. Suggestions for improving the implementation process were also provided. The completed Results Forms were generally correctly filled out and indicated an average of 3.4 contributing factors per investigation. Seven of the nine organizations continued to use an error investigation process after the field test. Since the end of the field test, the authors have provided MEDA implementation consultation to over 60 airplane maintenance organizations around the world. Feedback suggests that approximately two-thirds of the organizations are using MEDA.

Relevance to industry

The safety consequences and economic losses to the airline industry due to maintenance errors are very costly. A process for determining the factors that contribute to errors so that they can be corrected should help eliminate future, similar errors. The philosophy that situational factors contribute to error could also be applied in factory settings to investigate fabrication, assembly, and operational errors.

Keywords: Maintenance error investigation; Human error; Performance shaping factors; Contributing factors

1. Introduction

Airplane maintenance errors have safety and economic costs. A study by Boeing and the U.S. Air Transport Association members (Boeing/ATA,

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1995) found that maintenance error was one factor, typically among a series of factors, that contributed to 39 of 264 (15%) commercial jet aircraft hull loss accidents where five or more people were killed (or would have been killed if the flight had been a passenger, rather than cargo, flight) from 1982 through 1991. More specifically, in those 39 accidents:

- 23% involved an incorrect removal/installation of components,
- 28% involved a manufacturer or vendor maintenance/inspection error,
- 49% involved an error due to an airline's maintenance/inspection policy, and
- 49% involved poor design which contributed to the maintenance error.

In addition, these 39 accidents resulted in 1429 on-board fatalities.

One engine manufacturer, discussed by Rankin and Allen (1995), estimated the percentage of specific engine events caused by error and economic costs of those events to the airlines:

- 20% to 30% of engine in-flight shutdowns are caused by maintenance error and can cost an estimated $500,000/shutdown,
- 50% of flight delays due to engine problems are due to maintenance errors and can cost an estimated $10,000/hour of delay,
- 50%of flight cancellations due to engine problems are caused by maintenance error and can cost an average of $50,000/cancellation.

But can maintenance error be managed? A Boeing analysis of engine in-flight shut down rates on Boeing airplanes due to maintenance error (comparing 15 different air carriers with over 1,000,000 h of engine operation) found that the rates differed by a factor of sixteen between the lowest (0.0005 shutdowns/1000 h) and highest (0.008 shutdowns/1000 h) rates. Clearly, some airlines manage these types of maintenance errors better than others.

Given that maintenance error can have safety and economic impact, what can be found in the literature regarding errors and error prevention? The scientific study of human error began with a study of pilot error (Fitts and Jones, 1947). However, major interest in the study of human error began following the Three Mile Island (TMI) nuclear power plant accident in the spring of 1979. According to Woods et al. (1995), the international, inter-disciplinary study of human error began with the 'clambake' conference on human error in Columbia Falls, Maine, in 1980 and with the publications on slips and lapses by Norman (1981) and Reason and Mycielska (1982). In addition, work in the area of human reliability (e.g., Swain and Guttman, 1983; Swain, 1987), began in the late 1970s and accelerated following TMI (see Gertman and Blackman, 1994).

The studies dealing with factors that lead to error lend themselves to the development of a process for investigating errors and determining what actions need to be taken to prevent or reduce the likelihood of future, similar errors. However, in order to move in this direction, it is necessary to overcome the negative connotations about human error, which can hinder the in-depth study of the causes of error and error management (e.g., Lorenzo, 1990; Reason, 1990; Woods et al., 1995). Reason (1990) feels that people make attributions to the causes of human error, and these attributions most often are related to the person rather than to the environment. Reason (1990) discusses this phenomenon as the 'blame cycle'. He believes that we can only break out of the blame cycle if, among other things, we recognize that errors have multiple contributing factors and that situations or processes are often easier to change than people.

Woods et al. (1995) also are concerned about the prejudicial effect that comes from labeling a cause of an accident as human error. One reason is that attributing an accident to human error is often seen as the causal explanation for the accident. This can restrict the true investigation that should occur, which is to determine what interaction between the person, the equipment, and other situational variables lead to the error.

These situational variables have also received much investigation, especially by Swain and Guttman (1983) in their development of human reliability analysis tools. They called these situational variables performance shaping factors (PSFs), and they analyzed how PSFs affected human error estimates. They list three major types of PSFs within their framework:

1. External PSFs
   - Situational characteristics – e.g., heat, lighting, vibration, work hours, shift rotation, organizational structure, and supervisor behavior.
   - Job and task instructions – e.g., procedures, shop practices, and organizational policies.
   - Task and equipment characteristics – e.g., perceptual/motor requirements, control/display relationships, task complexity, and human/machine interface issues.
2. Internal PSFs – e.g., previous training/experience, personality, intelligence, motivation, attitude, gender differences, and physical condition of the person.
3. Stressor PSFs
   - Psychological stressors that directly affect mental stress – e.g., suddenness of onset, task speed, task load, duration of stress, high risk, monotony, and distractions.
   - Physiological stressors that directly affect physical stress – e.g., duration, fatigue, pain or discomfort, temperature extremes, radiation, vibration, and disruption of circadian rhythm.

Swain (see Lorenzo, 1990) and Bird and Germain (1996) believe that only 15–20% of workplace errors can be controlled by individual employees, while the remaining 80–85% are under the control of management. One important aspect of PSFs is that they are seen as contributing to the cause of human error. Thus, the concept of PSFs can be used to help break the blame cycle. An obvious second important aspect of PSFs is that they help indicate where changes are needed to reduce human error.

Thus, it is not surprising that the concept of PSFs is used as a basis of error reduction programs. Lorenzo (1990), in discussing a human error reduction program for the chemical industry, lists the Swain and Guttman (1983) PSFs and then discusses ways to enhance a given PSF in order to minimize human error. McDonald and White (McDonald, 1995; White, 1995a,b) looked at the PSFs that lead to airport ramp accidents and incidents and developed a ramp safety program based on changes to these PSFs.

The MEDA evaluation was conducted to determine whether a maintenance error reduction process, based on the PSF concept, could be developed and used to investigate maintenance-error-caused events and to propose corrective actions to reduce future, similar maintenance errors within airline maintenance organizations.

2. Methods

2.1. Development of maintenance error investigation process

Boeing staff, along with representatives from British Airways, Continental Airlines, United Airlines, the International Association of Machinists, and the U.S. Federal Aviation Administration, met over a period of 18 months to develop the Maintenance Error Decision Aid (MEDA) process for investigating maintenance errors at airlines. Two associated products were developed: a Results Form and a User's Guide.

The main investigation tool is the MEDA Results Form. The Results Form consists of five sections: (1) general information, (2) event, (3) maintenance error, (4) contributing factors, and (5) corrective actions. The general information section contains spaces to report such things as airplane identification information, engine type, the MEDA investigator, and date of the error and of the error investigation. The Event section contains a listing of potential events, which, if caused by maintenance error, would initiate a MEDA investigation. The events selected by the development team include flight delays, flight cancellations, gate returns, in-flight engine shut downs, air turn backs, aircraft damage, flight diversion, rework, and injury to maintenance technicians.

The Maintenance Error section lists the errors that could occur and lead to an event. The major error headings include: improper installation, improper servicing, improper/incomplete repair, improper fault isolation/inspection/testing, actions causing foreign object damage, actions causing surrounding equipment damage, and actions causing personal injury.

The Contributing Factors section contains situational variables that could contribute to maintenance error. The factors were categorized and presented in a manner recognizable and easily usable by airline maintenance personnel. Ten categories were used:

1. information – written or computerized information used by maintenance technicians in their job, e.g., maintenance manuals, service bulletins, and maintenance tips,
2. equipment, tools, and parts,
3. airplane design and configuration,
4. job and task,
5. technical knowledge and skills,
6. factors affecting individual performance – e.g., physical health, fatigue, time constraints, and personal events,
7. environment and facilities,
8. organizational environment issues – e.g., quality of support from other Maintenance and Engineering organizations, company policies and processes, and work force stability,
9. leadership and supervision – e.g., planning, organizing, prioritizing, and delegating work,
10. communication – e.g., written and verbal communication between people and between organizations.

The Corrective Action section first requires the investigator to list the existing procedures, processes, and policies in the maintenance organization that were intended to prevent the error, but did not (see Reason's 1990 barriers to error). A second section provides space for writing in potential corrective actions that would take place where the technician does his or her work. A third section provides space for writing in potential corrective actions that would take place in other parts of the Maintenance and Engineering organization at the airline (e.g., maintenance planning, maintenance engineering, or spare parts ordering).

A typical error investigation process currently used by many airplane maintenance organizations and the eight-step MEDA process are shown in Fig. 1. A few words of explanation are needed. First, the authors have found that in practice there are actually three variations on the 'typical' process. (1) some organizations stop after the second step on the flow diagram – they simply want to know which organization to 'charge' the error to for bookkeeping purposes. (2) some organizations use the depicted process, although the discipline can range from 'loss of face' to job termination. (3) some organizations carry out a more in-depth error analysis, although, in the authors' experience, the investigations are rarely carried out in a consistent manner or with structured consideration for contributing factors. These usually end with the maintenance technician promising 'never to make that error again'.

A few comments are also needed about the proposed MEDA investigation process. First, an event must occur in order to start a MEDA investigation. Second, although it is necessary to determine who made the error since a MEDA investigation is dependent upon an interview with this person (or persons), the MEDA Results Form does not include a place for the maintenance technician's name (the philosophy is 'blame the process, not the person'). Third, asking the maintenance technician to suggest potential corrective actions makes the maintenance technician part of the improvement process rather than simply the guilty party. Fourth, the interview in the fourth step may determine that other people or functions within the maintenance system contributed to the error (e.g., Stores did not have the needed replacement part and gave the maintenance technician an incorrect substitute part), so follow-up interviews may be needed. Fifth, the database mentioned in step six may be nothing more than a stack of filled out MEDA Results Forms, although database software is available for MEDA (Tools for Error Analysis in Maintenance© from Galaxy Aviation Corporation). Finally, the feedback mentioned in the last step is needed to show that something is being done with the investigation information and to ensure that everyone in the organization can learn/benefit from the process.

In addition to the Results Form, a User's Guide was developed to explain how to carry out a MEDA investigation using the Results Form and to provide examples of contributing factors to the investigators. Finally, a MEDA presentation was

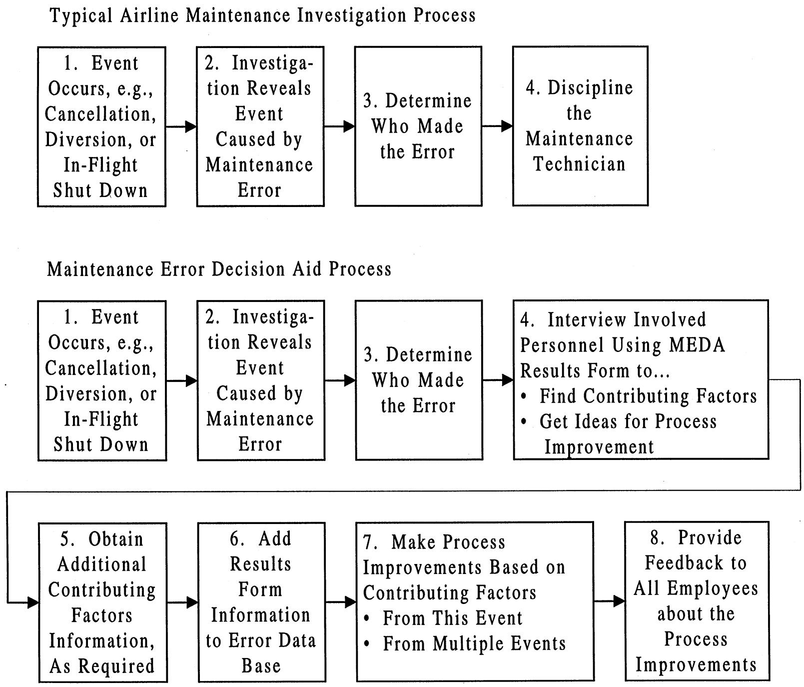

Fig. 1. Maintenance error decision aid process flow.

developed to present to airline maintenance management and MEDA investigators.

2.2. Participants

The MEDA process was evaluated at eight airlines and one repair station to determine its usefulness for investigating maintenance-error-caused events. The organizations that were included in the field test (along with their MEDA implementation support dates) included: All Nippon Airways (December, 1994); America West Airlines (March, 1995); British Airways (February, 1995); Continental Airlines (February, 1995); Northwest Airlines (January, 1995); Pemco World Air Services (March, 1995); Qantas Airways (March, 1995); Saudi Arabian Airlines (December, 1994); and United Airlines (November, 1994).

2.3. Evaluation methodology

Three different methods were used to collect evaluation data on the MEDA process. First, five questionnaires were used to collect opinion data. Before airline employees became MEDA investigators, they filled out the Field Test Survey, which collected baseline opinions about maintenance errors and the airline maintenance program. After carrying out a MEDA investigation, the investigator filled out the Tool Survey, which collected their opinions about using the Results Form. In addition, the maintenance technician, who made the error and was interviewed as part of the investigation process, filled out the Subject Survey, which collected their opinions about the MEDA process. Maintenance managers filled out a Management Survey, which asked about their acceptance of the MEDA process and about the perceived importance of the contributing factors. Finally, the investigators filled out the Follow-Up Survey, which restated many of the opinion items from the Field Test Survey.

The second evaluation method was an analysis of the completed Results Forms. The forms were reviewed to see if they were being filled out in the appropriate manner. In addition, the information supplied by the forms – event, error type, and contributing factors – were summarized. The third evaluation method was to hold meetings during and after the field test to get feedback from the MEDA contacts from the nine organizations.

3. Results

3.1. Survey results

Each of the five surveys contained various types of opinion questions. Only those questions that pertain specifically to the implementation of the MEDA process are discussed below.

3.1.1. Field Test Survey results

The Field Test Survey was filled out by 248 airline employees before they attended the investigator workshop. Respondents were asked a series of questions about the maintenance support environment (see Fig. 2). A large majority of respondents (77%) felt that written materials were available when needed, and a plurality of respondents agreed that lessons learned from maintenance error are shared so that they are less likely to occur again (48%), that technicians are kept informed about potential problem areas where errors are likely to occur (46%), and that written material is presented in understandable formats (43%). Fewer respondents agreed than disagreed that technicians receive effective support from other maintenance organizations (34% agree, 37% disagree), that technicians are not afraid to admit to errors (29% agree, 50% disagree), that technicians receive detailed feedback from their supervisors about task performance (22% agree, 54% disagree), and that maintenance technicians are satisfied with their working environment (29% agree, 50% disagree).

In addition, three opinion questions (not shown in Fig. 2) asked about punishment for errors. While 45% agreed that punishment is often used to discipline technicians for making errors, only 22% agreed that disciplinary actions are fairly applied

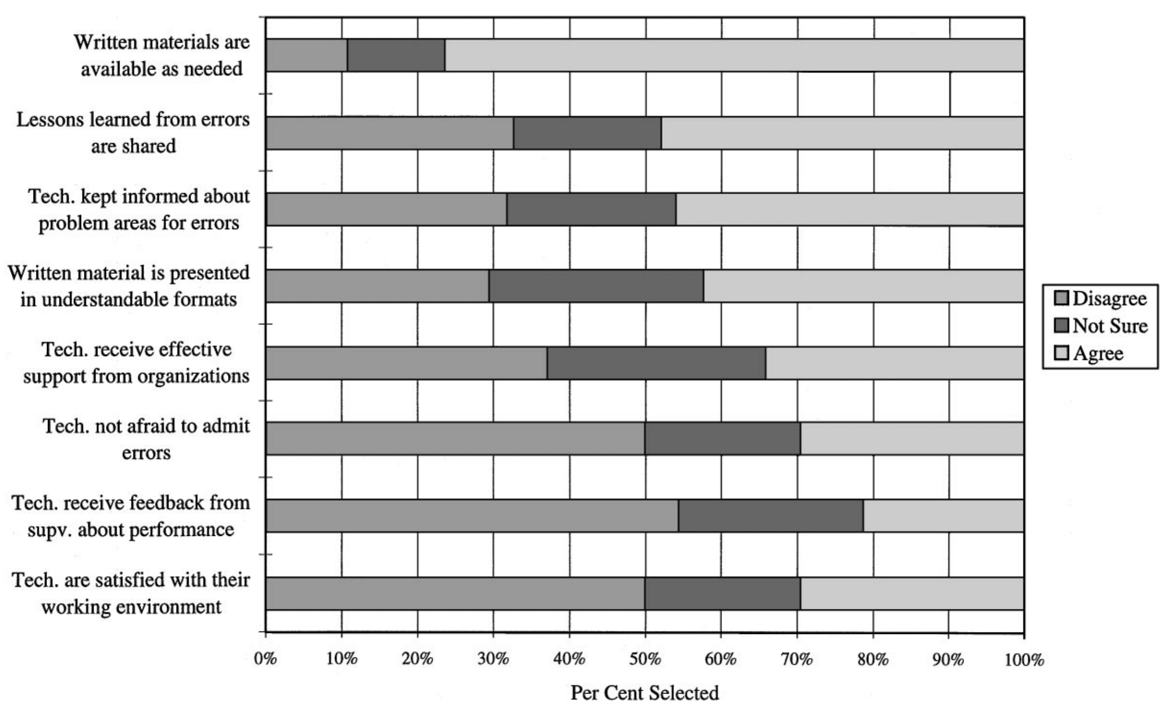

Fig. 2. Field Test Survey, $N = 248$. Percentage of MEDA investigators who selected agree, not sure, or disagree to opinion questions about their support environment.

and justified (43% disagreed), and only 9% agreed that punishment usually results in improved performance (63% disagreed).

Finally, one opinion question asked respondents what they felt was the biggest obstacle to maintenance error investigation in their job environment. Airline processes (32%) was selected most often followed by airline management (23%) and other employees (16%).

In summary, responses regarding the support environment suggested that the MEDA process would be useful at the airlines. For example, less than half the respondents believed that lessons learned from errors are shared, that written information is presented in an understandable manner, that technical support is effective, and that technicians are satisfied with their working environment. However, several opinions suggested that MEDA would have obstacles to overcome for implementation. For example, maintenance technicians were afraid to admit to errors, and punishment has been used in the past for errors. In addition, the respondents also felt that disciplinary actions were not applied fairly nor did the disciplinary actions result in improved performance.

3.1.2. Tool Survey results

The Tool Survey was filled out by 237 respondents after the investigator workshop or after their first MEDA investigation. There were six opinion items regarding whether the MEDA process is easy to use. A majority of the respondents agreed that MEDA uses familiar words and terms (85%), that MEDA documentation was understandable (83%), that MEDA documentation was complete (76%), that enough information was provided to learn how to use the MEDA process (69%), and that it is useful to list existing barriers to error that failed on the Results Form (67%).

Eight opinion statements were used regarding using MEDA for investigations (see Fig. 3). There was strong agreement that the results of the MEDA analysis were understandable (74%) and applicable (74%) and that the MEDA Results Form helped identify contributing factors (71%), technician error (63%), and corrective actions (57%). Cooperation from other employees during a MEDA investigation was not universally strong, as evidenced by the 52% not sure response to this statement. Overall, however, 65% of the respondents agree that they found MEDA easy to use.

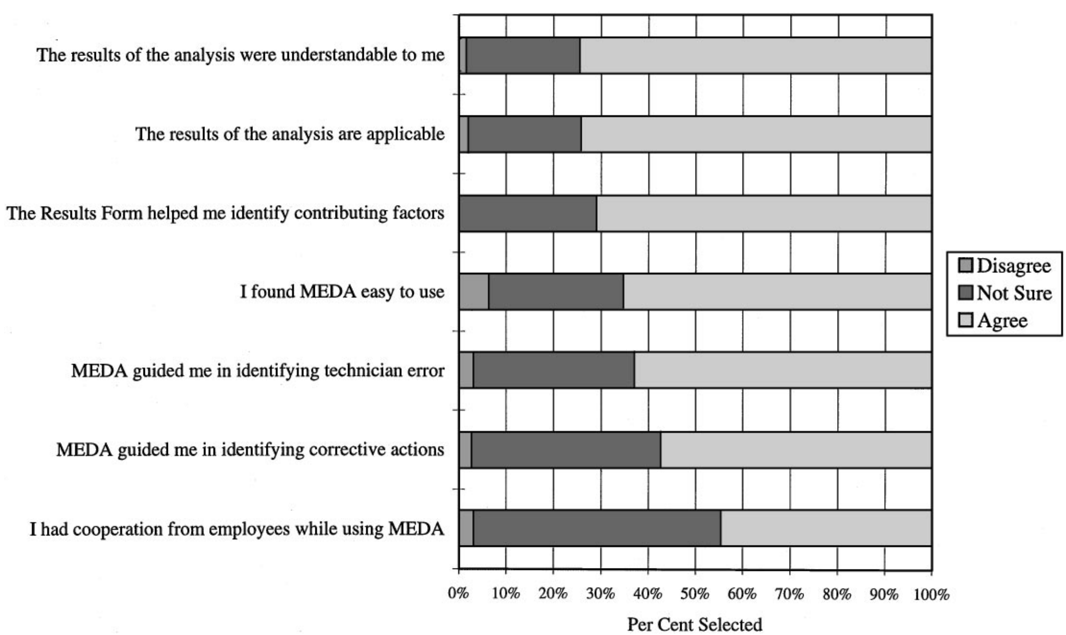

Fig. 3. Tool Survey, $N = 237$. Percentage of MEDA investigators who selected agree, not sure, and disgree to opinion questions about carrying out a MEDA investigation.

Nine opinion items regarding MEDA acceptance and likely usage were also asked (see Fig. 4). These items show a generally positive outlook tempered by uncertainty, as shown by the large% of respondents who selected the not sure category. There was strong agreement that MEDA will yield standardized results for analysis (75%), that MEDA could replace current maintenance error investigation methods (72%), that the job environment will improve as a result of MEDA (68%), and that maintenance error will decrease (58%). The respondents also believed that maintenance error investigations will increase (57%) and that MEDA will be supported by maintenance management (57%). However, there was great uncertainty about whether there will be less punitive actions for maintenance error because of MEDA (54% not sure), that MEDA would be accepted (53% not sure), and that MEDA would cause new corrective actions to be put in place (61% not sure).

In summary, 237 respondents filled out the Tool Survey. A majority of respondents believed that the MEDA Results Form helped them with their error investigation, that it was easy to use, and that MEDA will have a positive impact on their maintenance organization. However, they are much less certain that MEDA will reduce punishment for making errors or that it will cause new corrective actions to be taken – issues under management control.

3.1.3. Subject Survey results

Following a MEDA investigation interview, the Subject Survey was filled by the maintenance technician who was interviewed. Seventeen Subject Surveys were returned. Nine opinion statements were presented regarding the maintenance technician's involvement in the MEDA investigation (see Fig. 5). A majority of the respondents agree that they did not feel intimidated by the MEDA investigation (88%), that it was useful to discuss the existing barriers to error that failed (75%), that the purpose of MEDA was made clear to them (65%), that MEDA documentation was made available to

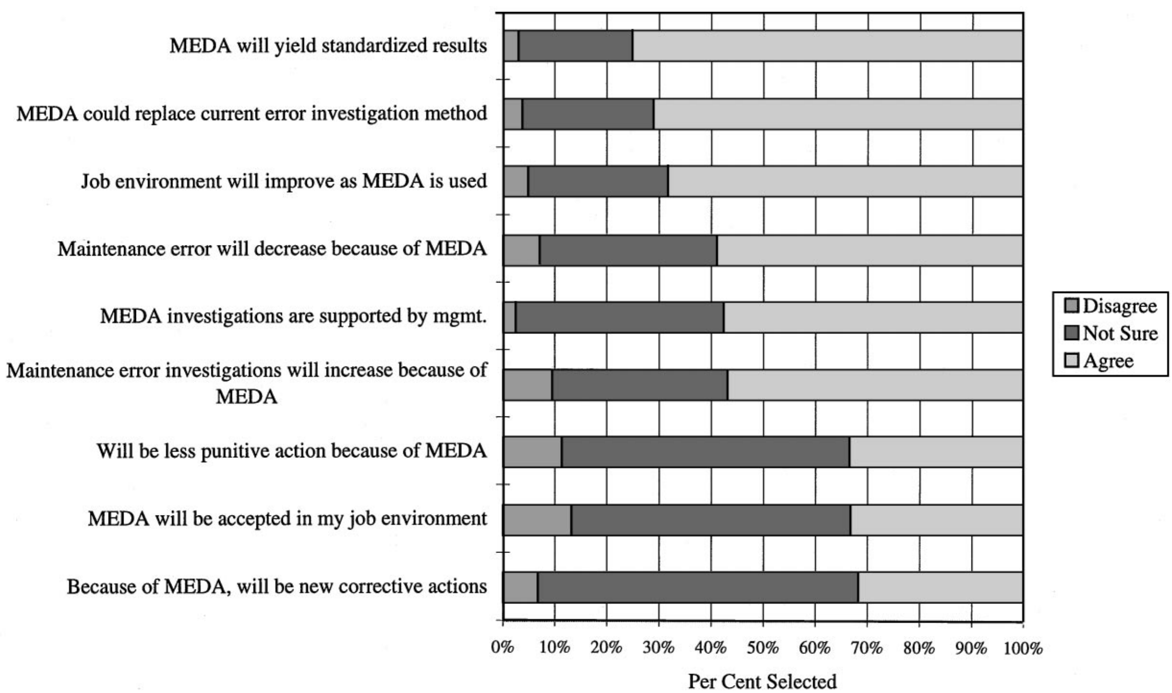

Fig. 4. Tool Survey, $N = 237$. Percentage of MEDA investigators who selected agree, not sure, or disagree to opinion items regrad MEDA acceptance and use.

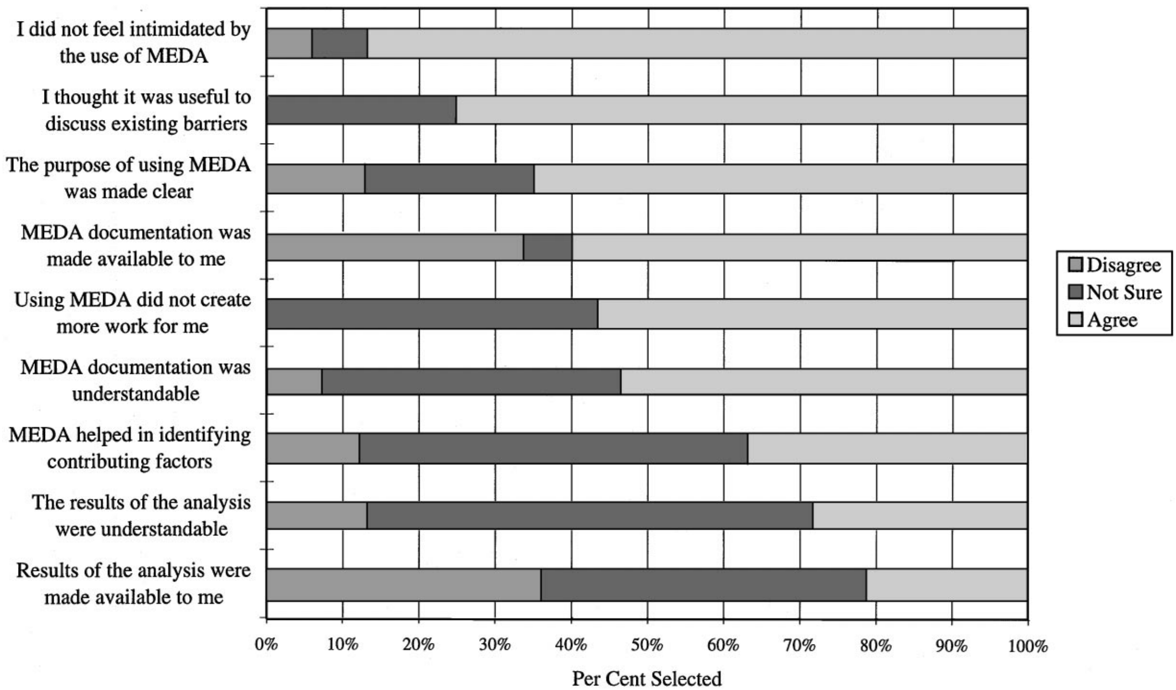

Fig. 5. Subject Survey, $N = 17$. Percent of maintenance technicians who selected agree, not sure, or disagree, on opinion items regarding maintenance technician involvement in the MEDA process.

them (60%), that MEDA did not create more work for them (57%), and that the MEDA documentation was understandable (53%). There was less agreement and more uncertainty regarding whether MEDA helped in identifying contributing factors to error (50% not sure), whether the results of the analysis was understandable (57% not sure), and whether the results of the analysis were made available to the technician (43% not sure). In summary, when maintenance technicians, who made the error, took part in the MEDA investigation, they usually had a positive experience.

3.1.4. *Airline Management Survey results*

The Airline Management Survey was filled out by one or two maintenance managers at each of the field test airlines at the end of the field test. Thirteen questionnaires were returned. Nine opinion items regarding understanding and acceptance were asked (see Fig. 6). Ninety-two% of the managers '…fully agree with the MEDA philosophy that most maintenance errors are not intentional, but are mainly a result of factors that contribute to error' and 67% agreed that they '…fully understand how MEDA error investigations were carried out at my airline during the field test'.

Fifty % of the managers agreed that their airline had done a good job in implementing MEDA for the field test, although 34% were not sure. Most (85%) agreed that there was strong acceptance of MEDA by their airline management, although only 42% of the managers agreed that there was strong acceptance of MEDA by their airline maintenance technicians (and 42% were not sure). Forty-two % agreed that they had seen positive benefits to their airline maintenance function as a result of using MEDA, although the remaining 58% were not sure. Seventy-seven percent of the managers agreed that they strongly support the continued use of MEDA at their airlines, 74% agreed that other airlines should adopt MEDA, and 69% agreed that it is important for airlines to share MEDA investigation results with each other. Thirty-eight % of the managers agreed that their airline would

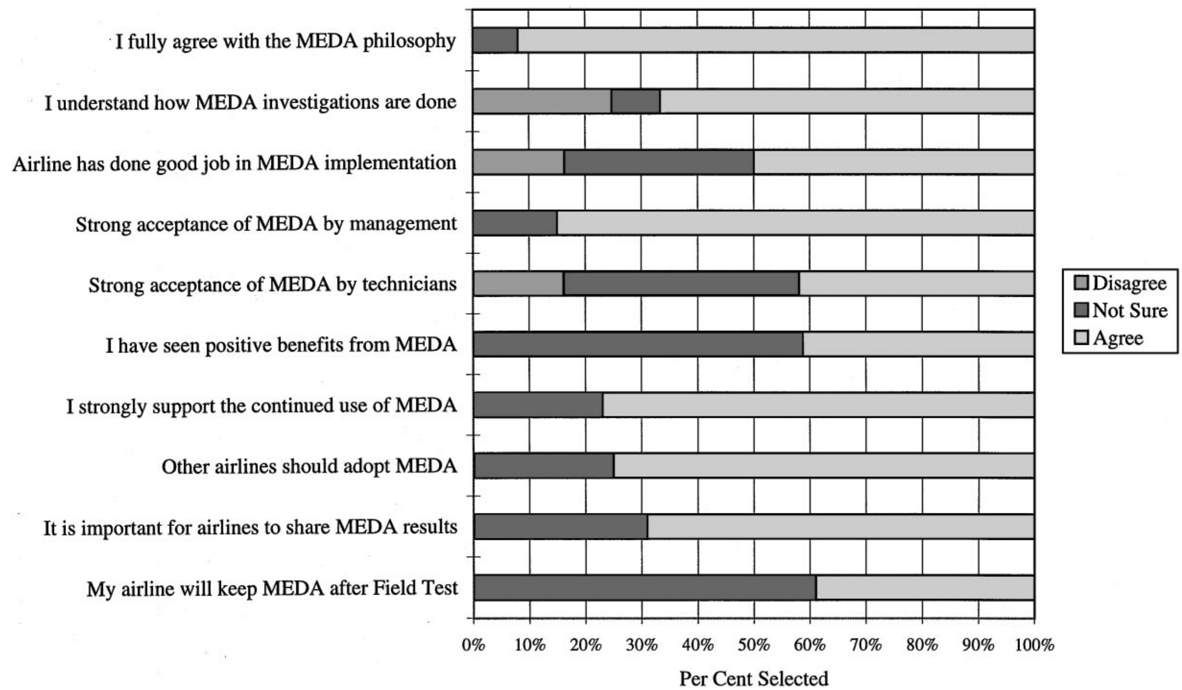

Fig. 6. Airline Management Survey, $N = 13$. Percent of airline managers who selected agree, not sure, or disagree to opinion questions about MEDA implementation issues at their airline.

continue to use MEDA after the field test, although the remaining 62% were not sure.

In summary, airline management agree with the MEDA philosophy, know how MEDA investigations are carried out, think that MEDA is positively accepted by airline employees, have seen positive benefits from MEDA, and strongly support the continued use of MEDA. However, they are unsure whether MEDA will continue to be used at the airline after the field test.

3.1.5. Field Test Follow-Up Survey results

The Field Test Follow-Up Survey was completed by 49 MEDA investigators during the last month of the field test (see Fig. 7). The questionnaire contained seven of the same questions that were asked of airline management. In comparing the Fig. 7 results with the results shown in Fig. 6, it is clear that the MEDA investigators are not as optimistic as airline management about the acceptance and continued use of MEDA.

Only 18% of the follow-up respondents agreed that their airline had done a good job in MEDA implementation, which is much less than the 50% agreement on the Management Survey ($p < 0.05$, one-tailed difference of proportions test). Similarly, the follow-up respondents indicated less agreement than the management on all of the questions: 43% of the managers vs. 17% of the follow-up respondents agree that there was strong acceptance of MEDA by airline technicians ($p < 0.05$, one-tailed difference of proportions test); 85% vs. 33% regarding strong acceptance of MEDA by airline management ($p < 0.05$, one-tailed difference of proportions test); 42% vs. 20% regarding having seen positive benefits from MEDA (n.s., one-tailed difference of proportions test); 77% vs. 56% on personal strong support regarding the continued use of MEDA at the airlines (n.s., one-tailed difference of proportions test); 75% vs. 45% regarding whether other airlines should adopt MEDA ($p < 0.05$, one-tailed difference of proportions test); and 38% vs. 22%

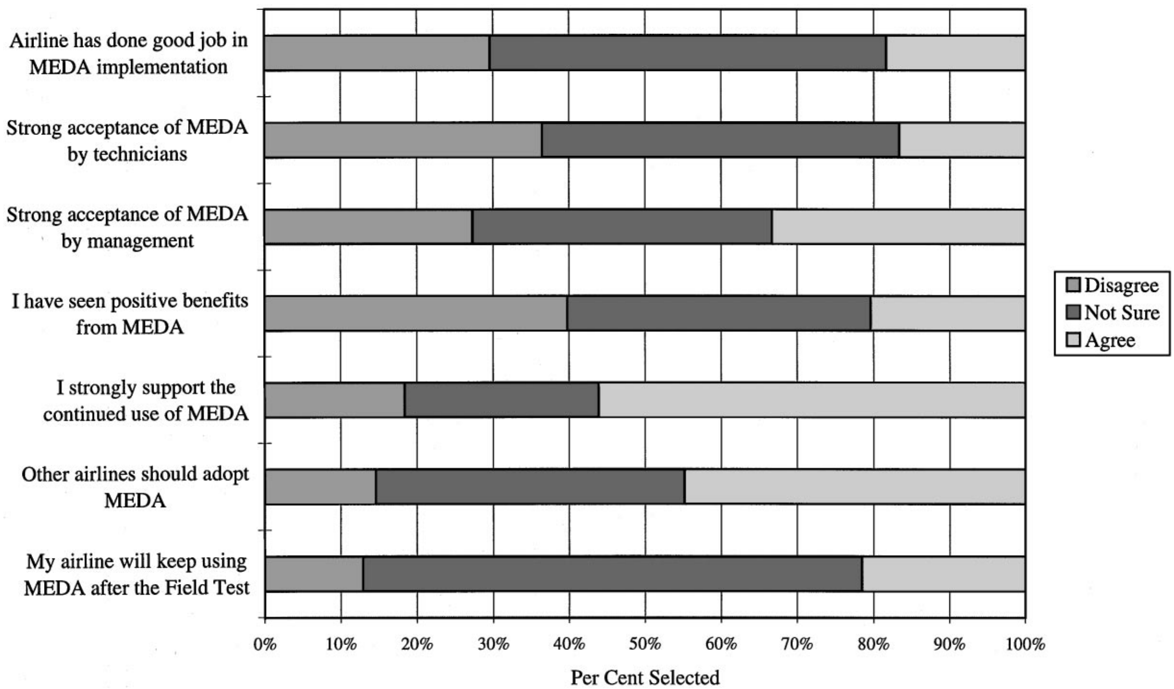

Fig. 7. Field Test Follow-up Survey, $N = 49$. Percent of MEDA investigators who selected agree, not sure, or disagree to opinion items also asked to airline maintenance management.

regarding whether their airline will continue using MEDA after the field test airlines (n.s., one-tailed difference of proportions test). Thus, MEDA investigators had less positive opinions about MEDA implementation and acceptance at the airlines compared to airline management, although a majority of the investigators strongly support the continued use of MEDA at the airlines.

3.2. Results Form results

3.2.1. Events

Seventy-four completed Results Forms were sent back for analysis. The frequency of the Operational Events that were studied were: flight delay (22 events), aircraft damage (17 events), air turn back (11 events), flight cancellation (7 events), rework (5 events), in-flight shutdown (4 events), gate return (3 events), injury (2 events), and other (11 events). The 'other' events included workshop errors, vendor problems, and a few events that probably could have been described by an existing event type, but were coded as 'other' by the investigators. The number of events added to more than 74, since more than one event could be caused by the error (e.g., in-flight shut down followed by an air turn back).

3.2.2. Maintenance error types

The types of errors that lead to the operational events included: improper installation (26 errors), improper fault isolation/inspection/testing (11 errors), improper servicing (9 errors), improper/incomplete repair (3 errors), actions causing foreign object damage (2 errors), actions leading to personal injury (1 error), other (17 errors), and no maintenance error reported (5 errors). Of the 17 'other' errors, eight were related to errors that caused ground damage. The no maintenance error recorded was an incorrect use of the Results Form.

3.2.3. Contributing factors types

The MEDA philosophy is that errors are caused by a series of contributing factors. The field test results supported this theory. For the 74 error investigations, information was a contributing factor to 37 of the errors, followed by communications (32), job/task (31), environment/facilities (28), factors affecting individual performance (26), technician qualification/skills (23), airplane design/configuration (22), equipment/tools/parts (20), organizational environment (19), and supervision (12). Thus, there was an average of 3.4 major categories of contributing factors per error event (250 contributing factors divided by the 74 error investigations).

3.3. Results of the field test feedback meetings

Two feedback meetings were held – one during the field test and one a month after the field test ended. The Results Form was felt to work quite well for error investigation, although several suggestions were made for improvements to it, including the need to rearrange the Results Form so that there was more open space on the form for investigators to write in.

In general, the major problem discussed was the difficulty that some of the airlines had in implementing the process. At least one airline had to 'restart' the program after their initial implementation. Two of the organizations involved never got the MEDA process implemented during the field test. All representatives agreed that it was very important that the process has a management champion to make sure that the program is implemented and continued.

The other important feedback was with regard to the support provided for MEDA implementation. The airline representatives suggested that three separate implementation sessions be provided. The first would be a presentation to senior maintenance management to briefly explain the investigation process and to specify clearly what the management responsibilities are in implementing the process. The second session would be a workshop for the MEDA investigators. It was suggested that the investigator workshop be lengthened and include practice in filling out the Results Form. The third session would be a meeting with the management responsible for implementation in order to lay out an implementation plan.

4. A case study example

4.1. Introduction

The following case study of Going Boeing Airlines (GBA) was based loosely on one of the field test events. In this case study an airline maintenance technician left debris in a fuel cell during fuel tank leak checks and repairs, which later resulted in a diversion and flight delay. A MEDA investigation was carried out following the event. This example has been used extensively by the authors during their MEDA implementation visits.

4.2. Case study

The GBA maintenance personnel involved included: (1) Scott – A licensed technician on third shift, 21 yr of age, two years experience, and above average height (6′1″) and weight (190 lb.); (2) Dennis – A licensed technician on first shift, 32 yr old, 10 yr experience, and below average height (5′7″) and weight (140 lb.); (3) James – A licensed, lead technician, 41 yr old, and 18 yr experience; (4) Bill – A licensed technician, now a maintenance quality control inspector, 52 yr old, and 30 yr experience in maintenance.

4.2.1. Event summary

A 767 was diverted to the closest airport when the pilot reported problems with the fuel flow indication system. After a delay, all 210 passengers were flown out on another airplane, which had been scheduled for an overnight check at that airport. Extensive troubleshooting, including defueling, purging and fuel tank entry for an inspection, revealed debris in the fuel tank. The debris included tape, gloves, and several rags. These had clogged some of the fuel lines. The debris had been left during fuel tank leak checks and repairs. It was not found by the inspector at the end of the check.

4.2.2. MEDA investigation

The MEDA investigation revealed the following information. Scott and Dennis were the two maintenance technicians who performed the fuel tank leak checks and repairs. Scott started the series of tasks during third shift. He used the Aircraft Maintenance Manual (AMM) as a reference to do the fuel tank purging and entry procedure. Then he started the area-by-area leak checks and repairs as shown by GBA work cards, using the AMM as a reference. Scott had trouble moving around in the tank because of his height, and this made him feel uncomfortable. He made minor repairs in some areas of the tank. Scott's shift ended before he finished the tank. Since Scott wanted to get out of the tank as soon as possible, he left the tape, gloves, and rags in the tank for Dennis to use on the next shift.

Scott checked off the tasks he had completed on the sign off sheets in front of each work card. He also wrote in the crew shift handover report which tank areas had been checked and repaired and which area he had last worked on. However, he did not write in the shift handover report nor did he tell his lead that he had not finished checking/repairing the complete tank and that he had left equipment in the tank.

James was the lead technician for the next shift. He read the shift handover report. He did not notice that Scott's work card was not signed off. So, he assumed that Scott's tank was finished and assigned the rest of the leak check and repair work cards for the other fuel tanks to Dennis. Dennis was the smallest member of his crew, and he found it easy to work in the fuel tanks.

Dennis completed the leak checks and repairs on the remaining tanks. Dennis saw that the AMM had recently been revised. Technicians were now supposed to count all the gloves, rags, and other equipment that were taken into and out of the fuel tanks to make sure that all equipment was accounted for. Dennis did not think this was needed, but followed the instructions because they were probably added for safety reasons. Dennis finished the remaining fuel tanks shortly before the airplane was due for final inspection. He signed off the remaining work cards and handed them over to his lead, James.

James (following a standard GBA procedure) put all of the fuel tank work cards together in one stack. Then he attached one inspection sign-off sheet to the outside of the stack. James handed this and other stacks of work cards to Bill for the final inspection.

The fuel tank access panels were still open when Bill did his inspection. He used a company-provided flashlight and mirror to inspect as much of each fuel tank as he could without going inside the tanks. This was an acceptable level of inspection at the airline. However, Bill could not see the entire area inside of each fuel tank from the access panel openings. Bill stated during his MEDA interview that the design of the fuel tanks made it impossible for him to see every area using the flashlight and mirror. He also said that the colors of the gloves, tape, and rags were almost the same color as inside the fuel tanks. Bill signed off the inspection sheet on the top of the stack of work cards. The fuel tank access panels were then closed up.

The MEDA investigation also found that the AMM procedures for the fuel tank purging and entry, fuel tank leak checks, and fuel tank repairs all contained instructions to make sure that all objects were removed from the tanks when the procedures were complete.

4.2.3. Completed MEDA Results Form Findings

Event. The event was a diversion followed by a flight delay.

Error. The main error was that debris was left in the fuel tank. A second error was that the inspector missed the debris on the final close-up inspection.

Contributing factors. The factors that contributed to these errors are listed below. In addition, it is indicated whether the factor contributed to leaving the debris in the fuel tank (debris) or to the inspector not seeing the debris (inspection).

- Information – the work cards had not been modified to instruct that everything going into and out of the fuel tank be counted (debris).
- Equipment/tools/parts – the tape, rags, and gloves were about the same color as the inside of the fuel tank (inspection).
- Airplane design/configuration – the baffles and structure in the fuel tank hid the debris from the inspector (inspection).
- Factors affecting individual performance – Scott was too big to move around easily in the fuel tank (debris).

- Organizational environment issues – company process allowed stacking of work cards, which contributed to no one noticing that Scott had not signed off (debris). Company process allowed less than a full fuel tank inspection (inspection).
- Leadership/supervision – fuel tank work was delegated to Scott, who was too big to move around easily in the fuel tank (debris).
- Communication – Scott did not tell his lead that he had not finished the fuel tank nor that he had left the materials in the fuel tank (debris). In addition, Scott did not write in the handover log that he had not finished the fuel tank nor that he had left materials in the tank for Dennis (debris).

Corrective actions. There were four failed barriers: (1) the final close-up inspection, (2) the maintenance manual, (3) the work cards, and (4) the shift handover log. Potential corrective actions that could be carried out by the inspectors, maintenance technicians, leads, and their supervisors (called a 'local' corrective action on the MEDA Results Form) include:

- Delegate fuel tank work to smallest maintenance technicians.
- Require a full entry inspection.
- Encourage better verbal communication and handover log write-ups.

Potential corrective actions that could be carried out in other organizations within maintenance and Engineering (called 'other' corrective action on the MEDA Results Form) include:

- Order brightly colored rags, gloves, and tape so that the material can be seen more easily.
- Add the "count things going in/out" steps to the work cards.
- Do not allow stacking of work cards.
- Add a sign-off block for the lead or inspector next to the maintenance technician's sign-off block so that a non-signed work card would be seen.
- Design inspection equipment that would allow the inspector to see all areas of the fuel tank from the access panel location.

5. Discussion

The MEDA process was successfully implemented at seven of the nine field test organizations. The survey data suggested that the MEDA philosophy was easy to understand and believed by the participants, that the MEDA training was adequate, and the MEDA Results Form was understandable and easy to use. The survey results, along with the feedback meetings, suggested that the organizations that implemented MEDA had received positive benefits from the error investigation process.

MEDA was easy to use once it had been implemented – the main problem was MEDA process implementation. Much of the information gained at the feedback meetings suggested that it was hard for management to put the various sub-processes (see Fig. 1) in place in order to get the overall MEDA process to work. That is why there was a strong felt need to have a management champion for MEDA at each airline.

The feedback sessions also suggested that airlines that had typically punished maintenance technicians for errors found it harder to implement MEDA than airlines that had not carried out (much) discipline for error. Since the MEDA process is dependent on the erring technician's willingness to be interviewed about the error, anything that would decrease this willingness, such as a fear of being punished for the error, would have a detrimental affect on MEDA implementation.

After the final field test meeting in August, 1995, the authors made improvements to the MEDA Results Form, User's Guide, and implementation process based on the airline representatives' comments. Then, Boeing announced its willingness to help customer airlines implement the process (Allen and Rankin, 1995; Rankin and Allen, 1995,1996). Since October, 1995 three of the authors have provided implementation consultation to over 60 additional airplane maintenance programs. These organizations have been encouraged to modify the MEDA Results Form and/or process in order to make it more useful to them. In January, 1997, the authors obtained feedback on maintenance organization use of MEDA in order to determine future implementation efforts. The results of the feedback

(Rankin et al., 1997) determined that approximately:

- one-third of the organizations had implemented MEDA as originally designed
- one-third of the organizations modified MEDA and then implemented their modified process, and
- the final one-third had not (yet) implemented MEDA.

The organizations using MEDA or their modified MEDA had all received positive benefits following implementation. These benefits ranged from sensitizing maintenance management to the causes of error to decreasing flight departure delays due to mechanical problems by 16%.

6. Conclusions

A maintenance error investigation process based on the performance shaping factor (contributing factor) concept can work in the commercial airline industry. Implementing the process requires strong management commitment. Carrying out the investigations and making corrective actions is relatively easy to do once the process has been put in place.

The results of the field test verify that the MEDA philosophy is correct – i.e., maintenance technicians do not make errors on purpose, errors result from a series of contributing factors, and many of the contributing factors are under management control and, therefore, can be managed. This error philosophy should also be applicable in other areas, such as the investigation of fabrication errors, assembly errors, and operational errors.

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